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Comunicações Avançadas com Fibra óptica Plástica

Advanced Communications with Plastic Optical Fibers

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Advanced Communications with Plastic Optical Fibers

Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Engenharia Electrotécnica / Telecomunicações, realizada sob a orientação científica do Doutor António Luís Jesus Teixeira, Professor Associado com Agregação do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro, e do Doutor Rogério Nunes Nogueira, Researcher do Instituto de Telecomunicações

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palavras-chave

Ffibra óptica de plástico, redes domésticas, multiplexagem por divisão de comprimento de onda, rede de Bragg em fibra óptica, formatos de modulação avançados, fibra de cristal fotônico.

resumo

Hoje em dia, a possibilidade de a fibra óptica até casa (FTTH) para a transmissão simultânea de diferentes serviços como internet, telefone, televisão digital é uma realidade. No entanto, para satisfazer as expectativas mais exigentes do usuário final com novos desenvolvimentos, tais como vídeo sob demanda, de alta definição (HD) e tridimensional (3D) de televisão (TV), computação em nuvem, vídeo conferências, etc., é necessário melhorar a infra-estrutura física da existente em redes domésticas, a fim de obter a melhor relação entre a qualidade do serviço e preço de implementação. Fibra óptica de plástico (POF) é considerada um meio de transmissão promissor para comunicações de curto alcance, queando comparadas com a clássica fibra óptica de silica (tanto monomodo como multimodo) e com as tecnologias atuais baseadas em fio de cobre. As principais vantagens da POF encontram-se na sua facilidade de instalação e conecção, possibilidade de uso de fontes e detectores de baixo custo, robustez e imunidade electromagnética. No entanto, o uso da POF de elevado diâmetro têm também desvantagens uma vez que esta oferece uma menor largura de banda e uma atenuação superior à fibra de sílica convêncional.

Esta dissertação de doutoramento tem como principal objetivo explorar as possibilidades de desemvolvimento de componentes de baixo custo baseados em POF para redes de curto alcance, com alta taxa de transmisssão de dados. Esta tese investiga a utilização de vários formatos de modulação combinados com equalizador e receptor, de maneira a superar as limitações de largura de banda em sistemas de comunicação óptica de curto alcance. Em particular, a modulação em amplitude de impulso (PAM) é proposta e investigada a fim de aumentar a capacidade de tais sistemas. Além disso, a possibilidade de usar múltiplos canais, utilizando uma única fibra óptica, também conhecido por multiplexagem por divisão de comprimento de onda (WDM), será analisada neste trabalho. A viabilidade das tecnologias de redes de acesso tanto a nível individual como em sistemas WDM serão analisadas usando componentes multimodo disponíveis comercialmente. A implementação será especificada em termos de desempenho tanto a nível da taxas máximas de transmissão, bem como na degradação do sinal que possa ocorrer na rede.

No capitulo 5 desta dissertação é apresentado sistema de radio através de fibra. Este tipo de sistemas permite a simplificação das estações base providenciando também uma elevada manutenção de custos. O principal objectivo deste estudo prende-se com a investigação do impacto da amostragem na preformance de digitalização de rádio através de fibra e também como a introdução de fibra óptica de plástico pode afetar o sistema.

Além disso, a possibilidade da aplicação de fibras óticas microestruturadas em redes de telecomunicações serão estudadas com ênfase principal na sua concepção estrutural. As fibras de cristal fotônico feitas de diferentes materiais altamente não-lineares com diferentes estruturas serão otimizadas a fim de alcançar uma dispersão ultra-plana, elevada não linearidade e baixa perda de confinamento em uma vasta gama espectral, na perspectiva de seu uso em aplicações de telecomunicações.

keywords

Plastic optical fiber, Home networks, wavelength-division multiplexing, Fiber bragg grating, advanced modulation formats**,** Photonic crystal fiber, Radio over fiber.

abstract

Nowadays, fiber to the Home/Curb/Building/Cabinet (FTTx) services that interconnect homes with a standard glass optical fiber cables to the core/access optical networks have brought the optical fiber at the doorsteps of our homes. However, the last few miles in home access network is still based on the limited bandwidth electronic component which supports by the cooper wires e.g. Cat-5, 6. The rapid growth of personal smart/mobile electronic devices with new developments such as video on demand, High Definition (HD) and three-Dimension (3D) television (TV), cloud computing, video conferences, etc. has been proposed new challenges for the next generation high bandwidth demand required for subscribers in home access network. In order to meet the more demanding expectations of the end user with new developments, it is necessary to improve the physical infrastructure of the existing in home networks in order to obtain the best ratio between quality of service and price of implementation. Plastic optical fibers (POFs) are point out as a promising transmission medium for short-range communication in compare to the “classic” single/multimode glass optical fibers and current cooper wire technology developments. The main advantages of POF are its easy to install, easy splicing and the possibility of using low cost optical transceivers, capability of being robust, and immunity to electromagnetic noise interference. However, the benefits of large-core POFs come at the expense of a less bandwidth and a higher attenuation than silica-based solution.
The main objective of this doctoral dissertation is to explore the possibilities and develop low cost, short reach, high data rate POF-links for in home networks applications. This thesis investigates the use of multilevel modulation in particular, pulse amplitude modulation (PAM in combination of the receiver equalizer in order to overcome the bandwidth limitations of the graded index POFs. The possibility of the using multiple channels over a single fiber to increase the capacity of POF systems using commercially available multimode components is also analyzed in this dissertation. Moreover, a low cost Digitised radio signal over plastic fiber system is proposed and evaluated to deliver digital baseband data for wireline and wireless users in home access network. The deployment will be specified in terms of performance, maximum rates and any degradation that might appear in the network.

Furthermore, the possibilities of the microstructured fibers in telecommunication application will be studied with main emphasis on their structural design. The photonic crystal fibers made of different highly nonlinear materials with different structures are optimized to achieve ultra-flat dispersion, high nonlinearity and low confinement loss over a broad range of wavelengths in the perspective of their usage in telecommunication applications.

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APD	Advanced Photodiode
AWG	Arbitrary Waveform Generator
BER	Bit Error Rate
BTB	Back-to-Back
CapEx	Capital Expenditures
CATV	Cable Television
CD	Coherent Detection
CAP	Carrierless amplitude phase modulation
DAC	Digital to Analog Convertor
DTD	Different time delay
DFB	Distributed Feedback
DFE	Decision feedback equalization
DM	Direct Modulation
DMT	discrete multitone
DSP	Digital Signal Processing
DWDM	Dense Wavelength Division Multiplexing
ECL	External Cavity Laser
EDFA	Erbium Doped Fiber Amplifier
EML	Electro-absorption Modulated Laser
ESA	Electrical Spectrum Analyzer
EVM	Error Vector Magnitude
FDTD	Finite-difference time-domain
FBG	Fiber Bragg Grating
FE	Finite Element
FEC	Forward Error Correction
FFE	Feed Forward Equalization
FTTx	Fiber to the Node, Curb, Building, or Home
FWM	Four-Wave Mixing
GE	Giga Ethernet

GPON	Gigabit PON
GOF	Glass optical fiber
GI-POF	Graded -Index Plastic optical fiber
HD-TV	High Definition Television
HAN	Home access network
HNLF	Highly Nonlinear fiber
IM-DD	Intensity Modulation – Direct Detection
ILMZ	Integrated Laser Mach-Zehnder
ITU-T	International Telecommunication Union Telecommunication
ISI	Intersymbol Interference
MZM	Mach-Zehnder Modulator
M-QAM	M-ary Quadrature Amplitude Modulation
MMF	Multimode fiber
M-POF	Microsturtued Plastic optical fiber
MMSE	Microstructured polymer optical fiber
MOST	Media Oriented system Transport
NA	Numerical aperture
NG-PON	Next Generation-Passive Optical Network
NRZ	Non-Return to Zero
OOK	On-off-keying
OFDM	Orthogonal Frequency Division Multiplexing
OOK	On-Off Keying
OpEx	Operational Expenditures
OFS	Optical fiber by Performance Standard
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal-to-Noise Ratio
OW	Optical Wireless
PAM	Pulse-amplitude modulation
POF	Plastic optical fiber

PBG	Photonic Bandgap
PCF	Photonic crystal fiber
PD	Photo Detector
PDF	Population Distribution Function
PDM	Polarization-Division Multiplexing
PMMA	Polymethyl-methacrylate
PON	Passive Optical Network
PRBS	Pseudo Random Binary Sequence
PSD	Power Spectral Density
PCF	Photonic Crystal Fiber
PF-GI-POF	Perfluorinated graded-index plastic Optical fibers
PtP	Point to Point
PtMP	Point to Multi-Point
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RAU	Remote Antenna Unit
RoF	Radio over Fiber
SSMF	Standard Single-Mode Fiber
SBS	Stimulated Brillion Scattering
SNR	Signal-to-Noise Ratio
SOA	Semiconductor Optical Amplifier
SPM	Self-Phase Modulation
SC	Supercontinuum Generation
TIR	Total Internal Reflection
TRx	Transmitter and Receiver
TWDM	Time and Wavelength Division Multiplexing
UDWDM	Ultra-Dense Wavelength Division Multiplexing
VCSEL	Vertical Cavity Surface Emitting Laser
VOA	Variable Optical Attenuator
VOD	Video On Demand

WDM	Wavelength division multiplexing
WDM-PON	Wavelength-Division Multiplexing Passive Optical Network
WS	Wave Shaper
ZDF	Zero Dispersion Fiber
X-GPON	10-Gigabit-capable Passive Optical Network
XPM	Cross-Phase Modulation
DROF	Digitalized Radio over Fiber
WiMAX	Worldwide Inter-operability for Microwave Access
WiFi	Wireless Fidelity

1 Chapter 1 Introduction, Objectives and Structure

1.1 Need for low-cost, high-performance and short-reach links

Nowadays bandwidth hunger is increasing vertiginously. Different on-line based applications are being developed, users are finding new ways of sharing information, new ways to get in touch. Social networks have arisen as worldwide platforms capable, in terms of software, of handling a massive range of information from tweets, to high definition videos, from music to e-books. Furthermore, new bandwidth hungry services are developed today, such as 4k high definition (HD) video and three dimensional (3D) videos, and such future applications as ultra- high definition video, web 3D, etc. will require a higher bit rate that will exceed the Gbps in the indoor network framework [1, 2].

These new applications start to be realistic, mainly after providing the high bit rate in the access network, with the installation of the Fiber to the Home/Curb/Building/Cabinet (FTTx) networks based on Passive Optical Networks (PON) [2]. The next generation passive optical network (PON) aims at 40 Gb/s downstream and 10 Gb/s upstream bandwidth [3,4]. The FTTx is defined as the access network architecture, where the final connection to the customer's premises is made using optical fiber. FTTH has seen much real advancement in broadband delivery at the access network in most developed countries. Statistics released by the FTTH Council in the year 2016 indicated that approximately 165 million users worldwide were already connected by optical fiber, the large majority of which were from the Asia Pacific Region with 115.8 million, followed by North America with 13.4 million, and Europe with 14.8 million users [4]. So, optical fiber allows high data rates from the core network to get all the way to the premises. Consequently, the FTTx services have brought the optical fiber at the doorsteps of our homes, but its huge capabilities are yet to be extended up to the user's devices inside home [5].

Currently, as shown in Fig. 1.1(a), there is a mixture of separate networks at homes, each optimized to provide a particular set of services. For example, coaxial cable is used for video and audio broadcast services; twisted pair is used for voice telephony; Cat-5E/6 is dedicated to data communication with desktop computers, printers, and data servers;

and Wireless Fidelity (WiFi) is widely used for laptops, tablets, smart phones, and other wireless devices. These multiple infrastructures for in-home networks cause a complicated consumer experience, expensive maintenance costs, and high-power consumption [6, 7]. Moreover, recent studies show as the demand for higher throughput increases by new developments, these cooper-based solutions have begun to reach their limits to satisfy the end high data rate user's needs [6-8]. For instance, cooper-based technologies suffer strong susceptibility to electromagnetic interferences and have limited capacity for digital transmission as well as the presence of crosstalk [7, 8]. Moreover, there is no cooperation between these networks exist. Therefore, it is not easy to upgrade services, to introduce new ones, nor to create links between services (e.g., between video and data).

In order to avoid these drawbacks as well as meet the more demanding expectation of the end user, a common backbone infrastructure [7-9], which can deliver all services in one single backbone and simultaneously keep the simplicity and low cost based on the optical fibers, is proposed in Fig. 1.1(b) [7-9]. In this scenario, all services are carried by a simple universal platform and distributed to each room. The role of the residential gateway (RG) is to provide an interface between the fiber to the home (FTTH) access network and the in-home network [8]. In principle, it should translate IP addresses and modulation formats to match them to the devices inside home [10].

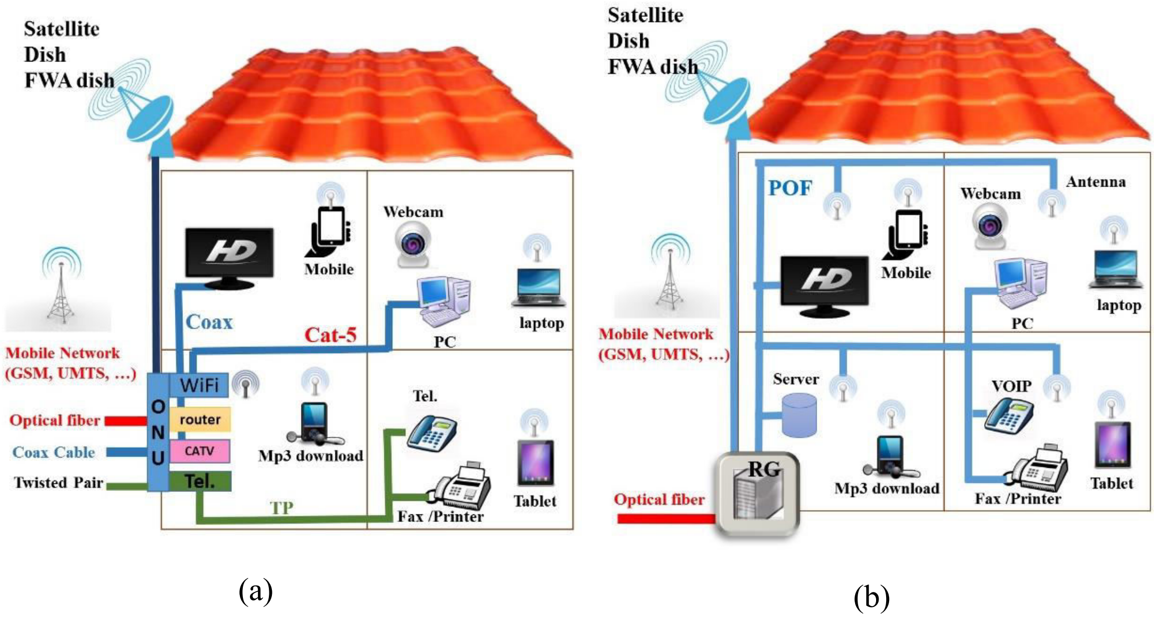

Figure0.1.1: In-home network infrastructures: current solution (a); ultimate solution (b).

The design of a universal communication link for home access network (HAN) is different from that of long-haul systems. Apparently, the design of home networks and their technologies needs quite a different approach from that of operator-owned outdoor networks. A significant part of the cost of the HAN and the components is provided by the end user (home owners) and therefore a challenge in designing network is the reduction of overall cost while retaining high bandwidth and always keeping the complexity low. Along with the cost of the components of the link, the packaging and installation play a key role in influencing the design [11]. As the main users of the in-home network is (mainly) unprofessional, the designed network should be easy to use ("plug-and-play") without requiring professional tools and expertise, the user decides him/her self which equipment to install [5-9]. So, the main technical challenges in enabling high-data-rate communication inside houses is providing the high quality of services in reasonable link-bandwidth and reach while simultaneously keeping the complexity and cost of systems low.

Traditionally, the classical glass optical fiber (GOF) seems to be the only candidate which has clear advantages over copper wire in terms of bandwidth, loss, and cross talk [12]. Single-mode fiber (SMF) almost entirely serves as the backbone of the any communication network because of its extremely low loss and large bandwidth, which are necessary for high-data-rate, long-haul systems [12]. However, to utilize their great performances in a network requires professional skills and tools for connecterization and installation. Hence, this is not a low-cost and user-friendly technology, which is the main concern of the in-building networks. An alternative technology is then the use of conventional silica-based multimode optical fiber (MMF) [5, 8] with larger core diameters. The large core of the MMF allows for easier light coupling from an optical source, large tolerance on axial misalignments, which results in cheaper connectors and associated equipment, as well as less requirements on the skills of the installation peoples [5, 6]. However, MMF provides the necessary bandwidth for short reach links in the access network at a length less than 10 km [7, 8].

In such short-distance applications in home networks (less than 500m), the extremely low attenuation and enormous capacity of a single/multi-mode GOF is unnecessary. Instead, simpler and less expensive components, greater flexibility, and higher reliability against bending, shocks, and vibrations are considerably more valuable properties [1-8]. Recently, Plastic optical fiber (POFs) [7] have emerged as potential solution for small office/home network deployments which provides many of 'user-friendly' benefits of the copper cables along with all the performance advantages of the fiber channels. POF offers several advantages over conventional silica multimode optical fiber in short distances applications. Such fiber type can provide an effective solution as its great advantage is the even potential lower cost associated with its easiness of installation, splicing and connecting [8-9]. This is due to the fact that POF have higher dimensions, larger numerical aperture (NA) and larger critical curvature radius in comparison with glass optical fibers [8]. Moreover, it is more flexible and ductile, making it easier to handle [9]. Consequently, POF termination can be realized not only faster but also cheaper than in the case of multimode silica optical fiber [10].

1.2 Why plastic optical fiber?

Plastic optical fiber (POF) has a history that even predates that of glass fiber, and yet it has been completely overshadowed by the glass fiber in the last decade [6]. The primary reason is the much lower loss of glass optical fiber (typically 0.2 dB/km for SMF and <3 dB/km for multi-mode fibers (MMF)) compared to the high loss of early POF generations (typically 200-1000 dB/km) [7, 8]. As a result, POF found application primarily in the automotive industry as a low-performance and short distance links [7, 8]. However, recent advances in the manufacturing process of POF has established it as an alternative to glass-MMF and copper links for short-reach and high-data-rate links [8]. In fact, conventional glass-MMF and POF both have the same basic advantages of a large-core fiber and they both are perfect candidates for home access networks. Compared to glass-MMF, POF has some other advantages, such as, potentially low component and overall system cost, ease of connectorization, and mechanical flexibility [9-12]. Furthermore, POFs are generally made with large core size (50 μm to 1 mm) that provides more tolerance in connectorization which makes their installation easy for unprofessional users. The POF connectorization can be done even with simple cutter and plug to POF system easily without need any training as can be seen in Fig 1.2. Moreover, POF offers large flexibility and ductility, which further reduces installation costs where this fiber can use the current power ducts installed in houses.

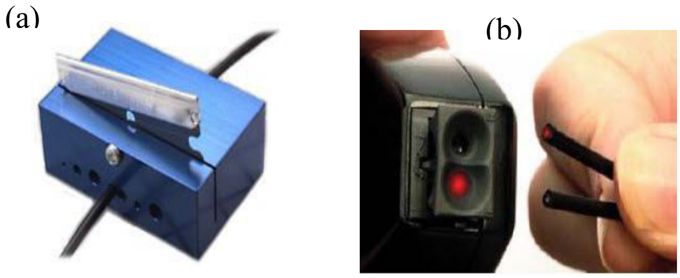

Figure 1.2: (a) Slice the POF cable (b) Split to the POF strands

There are several main advantages of using POF cables compared to conventional fiber cables or copper cables which can be highlighted as following:

- Easy to use (do-it-by yourself installation),
- No need for eye safety, splicing, cleaning and other connectorization issues,
- Lighter in weight – easier handling,
- Indifferent to electromagnetic interference,
- Smaller bend radius – inherent to thinner fiber.
- More importantly – cheap components

Until now, polymethyl-methacrylate (PMMA) has been the main choice to produce polymer optical fibers (POFs). Indeed, when compared with silica material, PMMA has a negative and much larger thermo-optic coefficient, smaller Young modulus [11], high water absorption capabilities [12] and biological compatibility [13]. These advantages are well attractive for sensor applications especially when large strains can be imposed in POFs without breaking the fiber [14]. Additionally, the use of microstructured polymer optical fibers (mPOFs) have attracted enormous interest, due to the ability to remain single mode (SM) in a large wavelength range [15] and the capability to control the modal properties, such as confinement loss and dispersion [9].

To summarize, POFs have multiple applications in sensor systems and short reach telecommunication at low or competitive cost compared to the well–established conventional technologies [10].

However, there are several issues that need to be addressed to make POF links a viable solution for short-reach in home network links. These issues include the bandwidth of large-core POFs [15], design of suitable transceivers [16], attenuation in POF and its impact on the power budget [17]. These issues are extensively explored to develop high-bandwidth, short-reach POF links.

1.3 Motivation and objectives

The main reason why POFs are not being completely installed in multi gigabit data rates home access networks is that due to the large dimension of the fiber core which results multimode transmission along the fiber. The constant refractive index in fiber core cause different velocities for all the modes transmitted which causes a narrow light pulse at the POF input to become a more widely dispersed pulse at the POF output [15-20]. 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. These phenomena limit the bandwidth, maximum link length and capacity of the POFs to attend future end users' transmission requirements [19, 20]. For in-home communication networks, because of the short link lengths, these disadvantages can be tolerated or compensated by applying digital signal processing [18]. Advanced modulation formats, such as pulse amplitude modulation (PAM), quadrature modulation formats, discrete multitone (DMT), and/ receiver equalization techniques are proposed to apply to such POF transmission systems to offer high capacity with an improved spectral efficiency [18–25]. In particular, the multi-level PAM modulation technology is intensively investigated in this thesis with combination of the receiver equalization. Beyond complex modulation formats in which the main goal is to provide a single channel communication link with a high spectral efficient (i.e. bit/Hz), one potential solution to expand the usable bandwidth of POF systems is to perform multiple channels over a single POF [26]. This technique is known as the wavelength division multiplexing (WDM) approach. Nowadays, WDM is well established in the infrared transmission windows for silica optical fibers in C + L telecommunication band, but this technique needs to be adapted to visible or infrared region (850 , 1310nm) for POFs due to their spectral attenuation behavior. And novel WDM POF devices and network topologies are necessary to a final success of POF in-home penetration. These devices include POF multiplexers/demultiplexers, variable optical attenuators, amplifiers, switches, plastic optical fiber Bragg gratins (POFBGs) and/or optical filters to separate and to route the different transmitted wavelengths. An important element in these systems is the Bragg grating. It is needed to filter and separate the different wavelengths at receiver side in order to obtain the signal information [27]. Moreover, Bragg gratings can be used in numerous other applications such as sensors, spectrum analyzers and fiber lasers [25, 26].

The radio over fiber system [27-31] is the most used solution to integrate the capacity of optical fiber with the flexibility and mobility of wireless networks to take advantage of enormous capacity of optical fiber with the flexibility and mobility of wireless networks. In a RoF system, the light is modulated by the radio signal in analog/digital domains and is transmitted over an optical fiber link from a central office (CO) to a number of base station (BS), where the wireless access points are placed. In this thesis, we experimentally propose and investigate the performance of the analog and digital radio over fiber systems over multimode GI-POF in home network scenario with coexistence of the 20km single mode fiber (SMF) in optical access network. The performance of the two technologies is also compared through analyzing the EVM.

Furthermore, the continuous and innovative theoretical and experimental works on the microstructured fibers shows that they possess fundamentally exceptional properties and over comes many limitations of conventional optical fiber, i.e. being endlessly single mode, high nonlinear coefficients, dispersion engineering and guiding light through hollow core [32-36]. Considering these unique as well as exceptional properties of the photonic crystal fibers (PCFs), we will study their applications in the telecommunication field. Analytical and accurate numerical tools will be employed to optimize their structures to achieve ultra-flat dispersion, high nonlinearity and low confinement loss over a broad range of wavelengths in telecommunication band.

This Ph.D. thesis aims to investigate the potential of the plastic optical fibers in next generation advanced communications in home access networks. Additionally, the application of the photonic crystal fiber in telecommunication field will be introduced and discussed. As such, the following objectives are envisioned for this dissertation:

1. Analyze the viability of the POF in point to point link configurations to support up to 10Gb/s transmission in home access networks.
2. Investigate advanced modulation formats to overcome the bandwidth limitation of the POFs, to be compatible with the specifications of future home access networks.
3. Investigate the combination of the receiver equalizer with multi-level modulation formats to overcome the bandwidth limitation of the POFs, which are compatible with the specifications of future home access networks.
4. Analyze the viability of WDM technology on POF to overcome the low data rates levels of a monochannel transmission. Fiber Bragg grating written in POFs will be used to filter the incoming signal to the receiver. The proposed solution should be based on the available components, and performance and costs will be evaluated to assess its viability for home networks.
5. Develop a simple model for digitised radio signal over plastic optical fiber to deliver digital baseband from wireline and wireless users in home access network to the 5G mobile front haul. Plastic optical fiber considered as a reliable, low networks capital and operational expenditure, and broadband backbone network

to connect the next generation home multi-cells/layers networks to the mobile front-haul.

6. Design photonic crystal fibers with specific dispersive properties, involving the zero-dispersion wavelength(s), dispersion magnitude and slope, by choosing appropriate nonlinear glasses and minimizing near field mode field diameter (MFD), while also taking into account the problem of confinement loss.

1.4 Organization of the thesis

Besides this introductory chapter, the remainder of this thesis is organized as follows:

Chapter 2 gives a brief introduction of the optical fibers in general with its especial emphasis on polymer optical fibers. The history of plastic optical fiber (POF) is presented and the different polymer materials used for optical fibers are summarized. The commonly used POF fiber types, such as the standard step index PMMA-based POF (SI-POF), the graded-index PMMA-based POF (GI-POF), and the perfluorinated graded-index POF (PF-GI-POF) are presented. The physical parameters and differences are discussed, which make them suitable for different short range interconnect application scenarios, such home networking. The optical properties of these materials and the POF are shown and the importance for home network application is explained.

Chapter 3 gives an introduction of optical data transmission systems based on plastic optical fibers (POF). The characteristics of available light sources and receivers for the use in the visible and infrared wavelength range are discussed and compared. Baseband transmission over POFs up to 10Gbps is experimentally evaluated. Then, in order to increase the capacity of the baseband transmission, the PAM-4 modulation in combination with electrical equalizer is numerically investigated and analyzed. Both experimental evaluation and numerical analysis are used to realize the maximum link length and high data rate over the PF-graded index POFs.

Chapter 4 presents the feasibility of the multiple transmission over POFs. The production and characterization of FBG in plastic optical fiber is described as well as the potential applications in optical communications and sensors. FBG technology can also be used to allow WDM over POF and, therefore, increase the capacity of POF communications without lowering the maximum transmission distance and keeping the costs relatively low. The viability of the WDM schemes over plastic optical fiber based on the commercially available passive optical components is analyzed.

Chapter 5 introduces the concepts involved in radio technologies studied on fiber (analog and digital), as well as the architecture of these and some experimental study of the digital radio over plastic optical fiber.

In **Chapter 6** firstly, an overview of the photonic crystal fibers is given**.** Then, optical properties and their application in telecommunication field is discussed. Analytical and accurate numerical tools will be employed to optimize the index guiding PCF structure. The index guiding PCFs made of different highly nonlinear materials with two novel structures will be optimized to achieve ultra-flat dispersion, high nonlinearity and low confinement loss over a broad range of wavelengths in telecommunication band.

Chapter7 summarizes the achieved results. Conclusions are drawn and recommendations for future research directions are stated.

1.5 Original Contributions

This Ph.D. thesis aims to investigate the potential of the plastic optical fibers in next generation advanced communications in home access networks. Additionally, the application of the photonic crystal fiber in telecommunication field will be introduced and discussed. As such, the following objectives are envisioned for this dissertation:

- The first part of the work, covering objective 1, 2 and 3 contributed to analyze the viability of the POF in point to point link configurations with commercially available multimode optical components to support up to 10Gb/s transmission in home access networks. The impact of advanced modulation formats with combination of the receiver equalizer to overcome the bandwidth limitation of the POFs, which are compatible with the specifications of future home access networks is also investigated.
- Secondly, objective 4, a special attention was given to implement the multi-channel over POFs. The viability of WDM technology on POF to overcome the low data rates levels of a monochannel transmission. Fiber Bragg gratings written in POFs are used to filter the incoming signal to the receiver. The proposed solution is based on the available components, and performance and costs will be evaluated to assess its viability for home networks.

- Next contributions, covering objective 5, was associated to the transmission of RF signals in conventional RoF systems to deliver digital baseband for wireline and wireless users in home access networks. The viability of the Digital RoF system to support the standard base band transmission in home access networks is also investigated. We experimentally investigate the impact of the ADC bit resolution on the performance of the DRoF system.
- The later part of the work, objective 6, addressed the numerical demonstrations of photonic crystal fiber applications in optical communicational. Two novel designs; namely hexagonal and spiral, are optimized to have zero dispersion and low dispersion in optical telecommunican C and L bands.

The thesis contributions can also be found in the following list of publications:

1. **J. Heidarialamdarloo**, R. Nogueira, R. Oliveira, & A. Teixeira "Viability of the Graded Index Plastic Optical Fibers in Home Access Networks", CONFTELE 2015, Aveiro, Portugal, Vol. 1, pp. 1 - 3, July 2015.
2. **J. Heidarialamdarloo**, A.N. Sousa, E. F. J. Silva, R.S. Oliveira, R. M. Ferreira, A. Shahpari, R.N. Nogueira, J. C.W.A. Costa and A. J. Teixeira, "Digitized Radio Over Plastic Optical Fiber for In-Home Network Applications", 26th International Conference on Plastic Optical Fibres, POF 2017 - Proceedings; Aveiro; Portugal; 13 -15 September 2017; Code131577.
3. R. Nogueira, R.Oliveira, L. Bilro, C. Marques & **J. Heidarialamdarloo**, "Recent advances in fiber Bragg gratings written in polymer optical fibers", Proc International Conference on Transparent Optical Networks ICTON, Budapest, Hungary, Vol. 1, pp. Th.A6.5 - Th.A6.5, July, 2015.
4. R. Nogueira, R.Oliveira, L. Bilro, C. Marques & **J. Heidarialamdarloo**, " Optical filtering in plastic optical fibers", Transparent Optical Networks (ICTON) 2013, 15th International Conference, vol., no., pp.1,4, 23-27 ,June 2013.
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6. J. Heidarialamdarloo, R. Oliveira, R. Nogueira, & A. Teixeira, M. I. Carvalho "Highly Nonlinear Dispersion Flattened Equiangular Spiral Photonic Crystal Fiber at the Telecommunications Window", Accepted in Journal of Lasers, Optics & Photonics, 2018.
7. R. Nogueira, R.Oliveira, L. Bilro & **J. Heidarialamdarloo**, "New advances in polymer fiber Bragg gratings:" Journal of Optics and Laser Technology, Vol. 78, No. Part A, pp. 104 - 109, April 2016.

1.6 Concluding Remarks

This chapter presented an overall view of the thesis. The motivation and b ackground for future optical access networks were discussed. The most relevant technical and economic aspects related to energy consumption, spectral efficiency and coexistence scenarios in design of these networks were highlighted. The original contribution of the thesis and thesis organization were presented.

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2 Chapter 2 Fundamentals of the POFs

2.1 Introduction

This chapter gives a brief introduction of the optical fibers in general with its especial emphasis on polymer optical fibers. The history of plastic optical fiber (POF) is presented and the different polymer optical fibers are summarized. The optical properties of the POF are shown and its importance for home network application is explained.

2.2 Optical Fibers

An optical fiber is a cylinder-shaped dielectric waveguide. A fiber consists of a core with a refractive index n_{core} and a surrounding cladding layer with a refractive index n_{clad} [1]. If the core index is larger than the cladding index, the light will be guided within the core due to total internal reflection at the core cladding interface. One of the key parameters of optical fiber is the acceptance angle of the fiber or numerical aperture (NA) which is determined by the two indices [2].

$$NA = nsin\theta_{max} = \sqrt{n^2{}_{core} - n_{clad}{}^2} \qquad (2.1)$$

Where, $\theta_{\max}$ is the maximum acceptance angle. The larger the value of NA, hence, the greater acceptance angle, the more amount of light the fiber can collect and the wider the output beam will expand from the fiber end. The boundary between the core and cladding may either be abrupt, in step-index (SI) fiber, or gradual, in graded-index (GI) fiber. As an optical waveguide, the fiber supports one or more confined transverse modes by which light can propagate along the fiber.

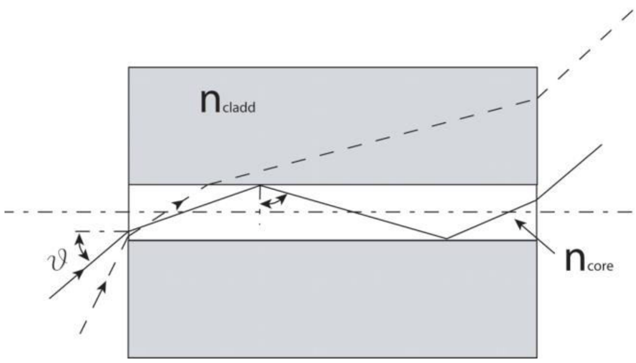

Figure 2.1: optical Fiber principle [1]

Another widely used key parameter is the V-parameter [3] which defines the mode volume of the core region in step index (SI) fiber,

$$V = \frac{2\pi a}{\lambda_c}\sqrt{n_{core}^2 - n_{clad}^2} = \frac{2\pi a}{\lambda_c} NA \qquad (2.2)$$

Where λ_c is the wavelength in vacuum and a is core radius of the fiber. For V values ≤2.405, a fiber supports only one mode per polarization direction (single-mode fibers). Multimode fibers can have much higher V numbers.

2.2.1 Single mode fibers

In fiber-optic communication, a single-mode fiber (also called mono-mode fiber) is an optical fiber which supports only a single propagation mode per polarization direction for a given wavelength. In a single mode fiber (SMF), the light basically travels along its axis. This eliminates the intermodal dispersion. For data communication, the absence of the intermodal dispersion increases the possible bandwidth as the pulse broadening due to different optical paths does not occur in SMFs. The standard single-mode fiber for telecommunication is the SMF-28E [4], which has a narrow core diameter of about 9 µm, a cladding diameter of 125 µm, and is used between the wavelength of 1310 and 1625 nm. The typical optical attenuation of the SMFs is about 0.2 dB/km at 1550 nm and 0.35 dB/km at 1310 nm which, together with the availability of optical amplifiers, allows for long-haul transmission [5]. Therefore, SMFs are used for high bandwidth applications over large distances, for example intercontinental data transmission. In long haul telecommunication system without any doubt they have the best optical performance, but there are some disadvantages included as well. The small core diameter of the SMFs makes them hard to connect and quite sensitive to bending. Moreover, their production cost is also relatively high and although most of these problems can be countered by thorough cabling and using special connection tools, they are still only used in high performance applications.

2.2.2 Polymer Optical Fiber

Polymer has attracted more attention as an optimal material for making optical fiber recently [6]. Polymer optical fiber has exhibited increasing potential in the future short distance moderate bandwidth data communication applications, for example, local area network [7], Fiber to the Home (FTTH) solutions [8], and high rate data transmission in automotive industry [9], etc.

2.2.2.1 Step index POFs

The step index plastic optical fiber (SI-POF) has a simple optical cladding surrounds a homogenous core. The first POF, with a step-index (SI) profile was invented by Du Pont in 1966 and Mitsubishi introduce the first commercialized SI-POF into the market in 1975, with Asahi Chemical and Toray following [10]. The typical SI-POF is large core multimode fiber made of polymethyl methacrylate (PMMA) with diameter up to approximately 1mm [12]. At this diameter, it can still remain highly flexibility, allowing easy handling and installation, good connectivity to low cost sources, such as light emitting diodes (LED), thanks to its large multimode core [15]. The large core SI-POFS have been widely used in industrial automation, more than 20 years in applications like PROFIBUS, INTERBUS, and SERCOS [15]. Furthermore, the SI-POF is the only type of the POFs which has been standardized. Media Oriented Systems Transport (MOST)[16] is a European standard that supports 100-500 Mb/s over POFs for interconnects in automobiles. Their main benefits are their robustness to electromagnetic interference and mechanical stress, the ease of installation and connection, the low weight, as well as the low price [15]. The principle of the light propagation through the SI-POF is almost the same as the Standard SMFs. SI-POFs are basically composed of two coaxial layers: the core and the cladding. The refractive index of a core (~1.49) is slightly higher than the refractive index of the cladding (1.46); therefore, the light propagates inside a core. In the SI-POF, there is a refractive index step between the core and the fiber cladding. In comparison to the SSMF, the large core of the SI-POF allows guiding more light in the large angle due to the large numerical aperture (NA) of 0.5, resulting in larger tolerances for bending and alignment [17]. However, the large numerical aperture, together with a small bandwidth-length product of around 50MHz ·100m, causes a strong modal dispersion. The source of the modal dispersion can be seen clearly in Fig. 2.2., where different rays are shown to travel along paths with different lengths.

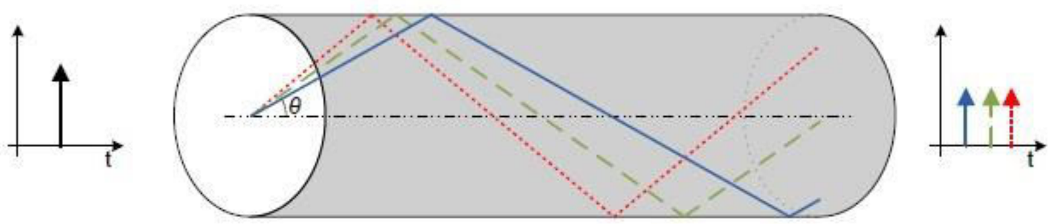

Figure 2.2: Light propagation in step-index multi-mode fibers [17].

The dispersion effect by multi-path propagation of different light mode shown by different colors in Fig. 2.2. Assume that the refractive index and velocity of the light inside the fiber is constant, the propagation time through the fiber is different for these three shown lights. This propagation time differences between the fastest and slowest light mode is known as a dispersion in time domain, which limits the bandwidth-length product of the SI-POFs to 50 MHz·100m [15].

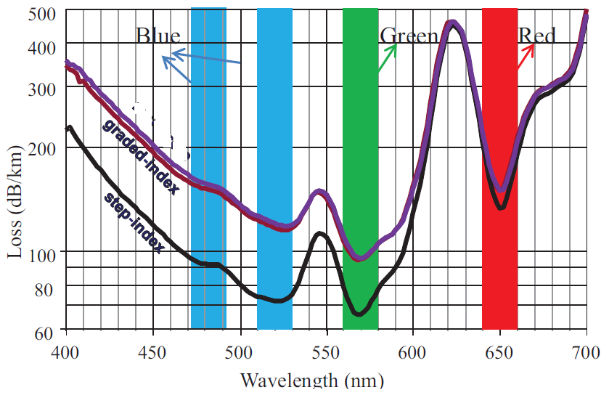

Figure 2.3: Spectral attenuation for the standard PMMA-based Plastic optical fiber [19].

The spectral attenuation curve for the PMMA SI-POF is shown in Fig. 2.3, where three transmission windows in a visible spectrum can be identified, namely at 520 nm, 570 nm, and 650 nm. The most commonly used window for data transmission is the red wavelength window at 650 nm, just because of the great availability of light sources (light-emitting diodes (LEDs) and laser diodes) and the good responsivity of the silicon-based photo diodes. The attenuation of the SI-POFs in this window is around 150 dB/km, which restricts the application to short-range communications to a range of a few 100 m. The two other transmission windows in the green and blue spectral range have much better attenuation values, but the available transmitter components have, up to now, much smaller modulation bandwidths compared to the ones in the red transmission window at 650 nm[15,16].

2.2.2.2 PMMA GI-POF

The PMMA-based graded-index POFs (GI-POFs) [17] have similar specifications as the SI-POF, except the gradient index profile (Fig2.4). These fibers with core diameters of about 1 mm have a higher bandwidth-length product of about 1.5GHz ·100m than the SI-POFs. On the other hand, in comparison to the SI-POF, they have a slightly higher attenuation of approximately 200 dB/km and a smaller numerical aperture (NA) of 0.23, which lead to higher bending losses [18]. They also have limited working temperature range from -30^0 to 60^0C which is too small for some specific applications [12]. The biggest difference of the graded-index POF (GI-POF) to the SI-POF is the light propagation inside the fiber core, which is illustrated in Fig. 2.4. The refractive index function n(r) is continuously decreasing inside the fiber core, from the highest value at the fiber center down to value at the cladding. This results in the curved light propagation, as it is depicted in Fig. 2.4. The effect is that the light modes traveling closer to the cladding have a higher velocity than those at the fiber core center. Therefore, the propagation delay difference between the fastest (the blue solid line) and the slowest (the red dotted line) light mode is minimized, which results directly in a smaller modal dispersion or equivalently in a higher bandwidth.

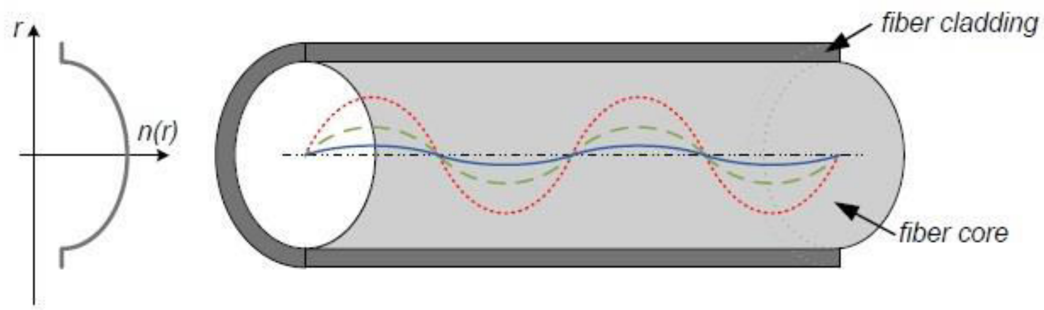

Figure 2.4: Light propagation in graded-index multi-mode fibers [18].

2.2.2.3 PF-GI-POF

The PF-GI-POF is a grade index plastic optical fiber which is composed of an amorphous perfluorinated polymer (commercially known as CYTOP). It firstly was developed by Asahi Glass in Japan [20]. The core diameter of the PF-GI-POF is varying from 50 and 62.5 µm to up to 120 µm. The PF-GI-POF has a smaller material dispersion than the silica fiber or the PMMA based POFs [18]. In comparison to the PMMA POFs, the PF-POFs provide a larger bandwidth as well as lower loss in the near-infrared wavelength range at commercially desirable 850 and 1310 nm wavelength range. The attenuation profile of the PF-GI-POF made by Chormis.Fiber co., which can be found in Thorlabs, is shown in Fig. 2.5.

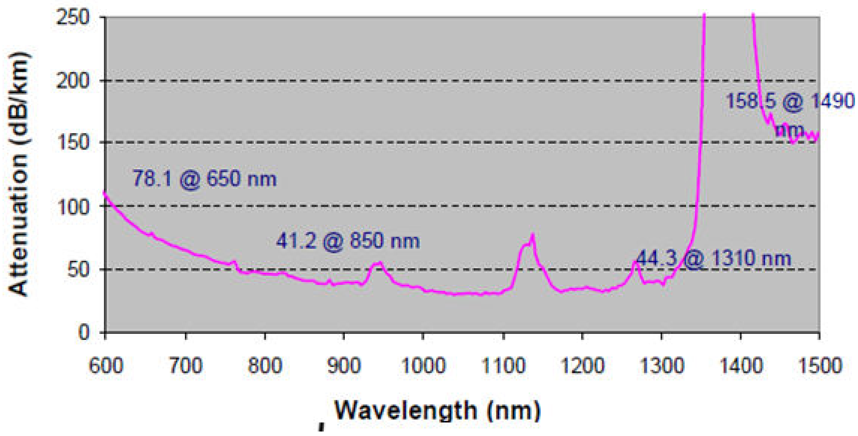

Figure 2.5: Spectral attenuation for the perfluorinated graded-index POF (PF-GI-POF) [21]

As shown in this figure, the attenuation of the PF-GI-POF in infrared region for both 850 and 1300 nm wavelength is lower than 50dB/km, which gives this type of the fiber an opportunity to use the optical transceivers and other devices of the silica multimode fibers in infrared region. Moreover, in contrast to the silica MMF, the PF-POF has more relaxed tolerance in terms of alignment, bending radii, stress, and enables simpler connectorization. The bandwidth-length product at a wavelength of 850 nm is about 3GHz.km. Accordingly, these types of the POFs are promising candidate to replacement of the MMF for short-reach optical fiber applications, where the coupling and connecterization are not big issues. Especially, more relax to bending ratio and mechanical stress are big advantages for optical cables.

2.2.3 Microstructured POFs

Standard single mode fibers (SSMFs) are often considered to effectively infinite capacity in the long haul backbone telecommunication systems. Specially designed optical fibers are also used for a variety of other applications, including sensors, fiber lasers, medicine and nonlinear optics. However, despite the relatively low losses presented by standard fibers, they have some fundamental limitation [22-25]. First, due to propagation of light in bulk medium (doped germanium) they are suffering from the nonlinearity such as absorption losses and radiative attenuation (Rayleigh scattering). Secondly, they have a fix geometry, so the dispersion characteristic of these fibers is restricted in some specific wavelengths (zero dispersion at 1310 nm for SMFs and 1550 nm for zero dispersion fiber (ZDF) and their dispersion cannot be easily engineered. Finally, they are not suitable for different requirements and applications such as high-power delivery, nonlinearity tailored and high birefringence requirements [24, 25]. To overcome with this problem, a new class of optical fiber, the photonic crystal fiber (PCF) developed in early 90s. PCFs also known as a microstructured fibers (MFs), was founded by Russell and coworkers in1995-96 [26]. In a PCF the fiber core is surrounded by a microstructured cladding, typically consisting of air holes arranged according to a given geometry. PCFs are classifying in two different ways by their guiding mechanisms: index guiding fibers and photonic bandgap fibers. In index guiding or solid core fibers light is guided by the modified total internal reflection (MTIR) mechanism which is quite similar to the guiding mechanism in standard single mode fibers. Light in index fibers is guided in a higher index core (generally pure silica), which results in light being confined into a small area. Due to the resulting high intensity of light into small mode area, the fiber can show a highly nonlinear behavior. The nonlinear parameter can be further enhanced if the fiber is made using glasses with higher nonlinearities than silica, such as sulphur hexauoride, lead silicate, tellurite, bismuthes oxide, and chalcogenide glasses [27, 28]. The microstructured cladding of the index guiding fibers offers greatly enhanced design flexibility and can manipulate the dispersion characteristics by controlling structural parameters such as the air-hole diameter and the hole-to-hole spacing (pitch). Such dispersion engineering allows the PCF to be designed with a at dispersion profile over the wide range of the wavelengths from visible region to telecommunication band [29, 30]. In these fibers a zero-dispersion wavelength can be found anywhere from (1550nm) down to 560 nm [29, 30].

Index guiding PCFs which can tailor zero dispersion with a low dispersion slop, high effective nonlinearity and low confinement loss can be used for optical signal processing applications at telecommunication window, such as flatten supercontinuum spectrum generation [30], wavelength conversion in high speed WDM optical networks [31], Four wave mixing (FWM) based switches [32] and so on. On the other hand, when the PCF core region has a lower refractive index than the surrounding photonic crystal cladding, light is guided by a mechanism different from the total internal reflection by using the photonic bandgap (PBG) effect [34].

In PBG fibers also known as hollow core fibers, the core can fill with air or other materials such as gas or liquid. Due to very low scattering and absorption loss in the air, the air core PBGFs have potentially lower loss than the SMFs or index guided fibers, which makes them a good candidate for transmission line in the future ultrahigh capacity systems. Since the PCFs first demonstration, they have been the subject of an intense research activity by the most important groups all around the world. PCFs with unusual guiding, dispersion and nonlinear properties can be designed and successfully used in various applications ranging from nonlinear optic devices to optical fibers.

2.2.3.1 Index guiding PCFs

Index-guiding PCFs also known as holey fibers are solid-core fibers in which light is guided by modified total internal reflection, in a process like the guiding mechanism of SMFs [35]. Light in holey fibers is guided in a higher index core, which results in light being confined into a small area and implies a highly nonlinear behavior of the fiber. The high index difference (~1.46:1 for pure silica) between the silica core and the air-filled microstructure cladding enables tight mode confinement resulting in a low effective area and, thereby, a high nonlinear coefficient. Generally, index guiding PCFs are made with single pure silica glass instead of using different materials for the core and the cladding as standard single mode fiber uses. Another important difference between index-guiding PCFs and standard fibers is that for index-guiding PCFs the microstructued cladding can lead the high design flexibility for various applications, while this does not hold for standard optical fibers [36]. The cross section of a typical PCF is presented in Fig.2.6, where the ail holes are defined as a hexagonal structure with hole to hole separation of the Λ. Highly nonlinear index guiding fibers with low confinement loss and controllable dispersion profile can be used for many nonlinear optical applications, such as supercontinuum generation, 2R regeneration, parametric amplifiers, four-wave mixing (FWM)-based switches, all optical signal processing, wavelength conversion, etc. [37-40].

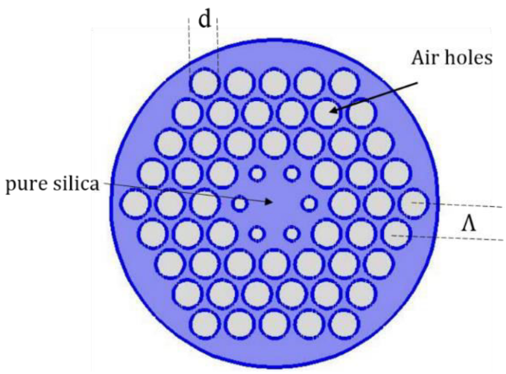

Figure 2.6: General schematic of the PCF

2.2.3.2 Photonic bandgap fibers

A novel class of photonic crystal fibers which called photonic band gaps (PBGs) or hollow core fibers was first demonstrated in 1999 has opened up new ways to guide flow of light [23]. In hollow core photonic crystal fibers the PBG effect allows for propagation in a low-index medium such as air or vacuum [30]. Due to the low index in the air region the total light power is confined to the air core rather than in glass, which can reduce the optical nonlinearities by a factor of 1000 as compared to the standard single mode fibers [41]. For that reason, these fibers present radically new optical characteristics, such as an extremely large effective area, low nonlinearity and a potentially low transmission loss over a broad range of wavelengths [42]. The other important issue that present by these fibers is widening the bandwidth, where they can utilize a new band, namely 1.0 μm band (T-Band) as the next generation band [43]. Since SMFs have λ_c around 1250nm, it is difficult to use T-band with SMFs. However, until now the lowest loss reported for the PBGFs is 1.2 dB/km [44] which is still higher than the typical loss value in the standard single-mode conventional optical fiber of approximately 0.2 dB/km. Even though there is a debate concerning their ultimate capacity, losses and the practical advantages offered by their extremely low nonlinearity [22], these fibers might have the potential to replace conventional fibers in future high capacity and ultra-wideband telecom transmission systems [45,46].

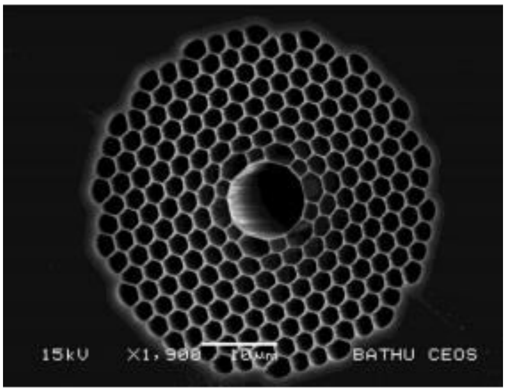

Figure 2.7: hollow core Photonic band Gap fiber [41]

2.2.3.3 Microsturtured polymer optical fibers

In the recent years, the microstructured polymer optical fiber is innovated on the basis of the success of photonic crystal fibers, [47] which utilize a pattern of multiple small air holes that run longitudinally through the entire length of the fiber to guide the light. This kind of fiber owns several important advantages over conventional POF such as ability to remain single mode (SM) in a large wavelength range [49] and the capability to control the modal properties, such as confinement loss and dispersion [50]. The mPOF can be fabricated from a single polymer. The different types of polymer materials, i.e. PMMA which is highly transparent, low cost and widely used in POF; fluorinated polymers which have lower material absorption [51]; TOPAS cyclic olefin copolymer (COC) which has less water absorption [52]; Polystyrene (PS) which has a higher refractive index [53]; polycarbonate (PC) which has a higher glass transition temperature (Tg) [52]; and biodegradable materials [54], etc., gives the potential to change various properties of microstructured POFs 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.

2.3 Optical properties of POFs

In this section, I briefly explain the different physical effects that happen during light propagation down a POFs.

2.3.1 Attenuation

In every optical fiber cable, the laser light that travels along a straight optical fiber cable experiences a power loss. This power loss is known as attenuation and as a rule of thumb [55], the power decreases as the distance of the optical fiber increases. The decrease in optical signal power is exponential to the distance of the optical fiber and has the formula expressed as [55, 56]:

$$P(l) = P(0)\times 10^{\frac{-\alpha . l}{10}} \text{ , (2.3)}$$

Where l is the symbol that represents the length of the optical fiber and α is the attenuation coefficient of the optical fiber. The equation 2.3 can be written in another way to:

$$\alpha = \frac{-1}{L} 10.\log \frac{P(l)}{P(0)} \text{ dB/km , (2.4)}$$

Attenuation is caused by interactions of the light with the material and can be subdivided into two categories: intrinsic and extrinsic losses [55]. *Intrinsic losses* are caused by the material itself and cannot be changed, unless another material is chosen. Examples are Rayleigh scattering and absorption through electronic transitions and molecular vibrations. On the other hand, extrinsic losses are caused during the manufacturing process and can be avoided, in theory [56, 57]. 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. Great efforts lowering the attenuation of the POF have been devoted in 1980s 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 Fig 2.4. [58]. The attenuation of the **first POF** developed by Du Pont was around 1000 dB/km. This was mainly due to the undeveloped 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 .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.

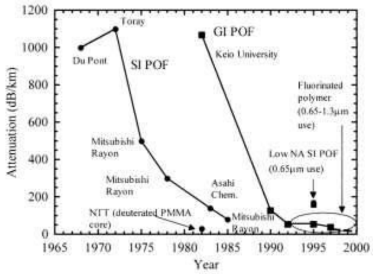

Figure 2.8: Development in the attenuation of POF [58]

The first **GI- POF** proposed from Keio University in 1982 [59] 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 [59]. Investigation of new polymer materials has been simultaneously performed to decrease the attenuation of the GI POF. In 1990s, 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 decreases 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 [60]. However, the large attenuation problem is still there and has not been solved. 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 [60]. 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 850 nm. The attenuation spectra for different optical fibers are shown in Figure 2.5.

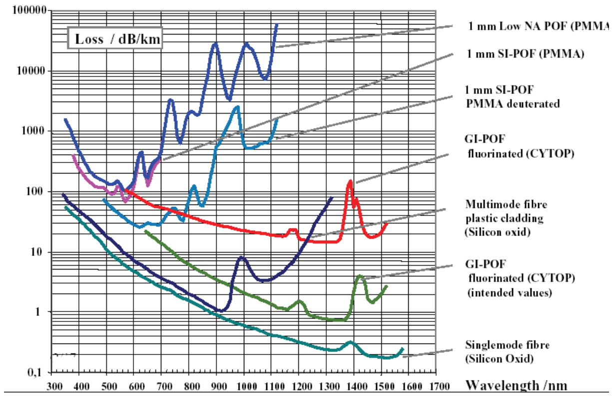

Figure 2.9: Attenuation Spectra of various Optical Fibers [61]

2.3.2 Dispersion and Bandwidth

Dispersion refers initially to all processes that broaden an input signal when it propagates through an optical waveguide. All parameters that describes the light (wavelength, polarization), can have different interactions with the physical medium, leading to differences in the propagation velocity. Moreover, all the possible modes have a different pathway, and therefore a different transit time. As a result, the width of a single pulse, as shown in 2.10 will increase.

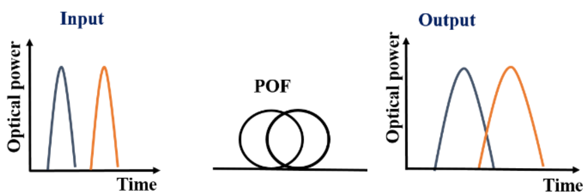

Figure 2.10: Dispersion in POFs

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). The two main causes for pulse broadening will be discussed separately: mode dispersion and chromatic dispersion (which can be subdivided into material dispersion, waveguide dispersion).

2.3.2.1 Modal Dispersion

For a multimode fiber, the most important cause of dispersion originates from the transit time differences of the modes. Since the light paths have different lengths, the pulses that have started simultaneously arrive at different times at the fibers output, a fact that leads to pulse broadening. The propagation times of the two different propagation paths are determined purely geometrically for [61]:

$$\Delta T_{Mod} = \frac{L}{2.C.n_{cladding}} \sim \frac{L.n_{core}}{C}.\Delta\ , (2.5)$$

Where $\Delta = \frac{n_{core} - n_{cladding}}{n_{core}}$ and L is length of the fiber. 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 NA= 0.5, a differential time delay of $\Delta T \approx 25\ ns$ for 100 m is produced which correspones to 20 Mb/s * 100 m of the bandwidth [62]. For Gaussian shaped pulses the following approximate relation between the transit time difference and the bandwidth can be used [62, 63].

$$B \approx \frac{0.44}{\Delta T}, \qquad (2.6)$$

To obtain high communication speeds, the bandwidth must be as large as possible.
There are few solutions to reach this goal. In equation (2.5), the dependence on the relative refractive index difference between core and cladding is already expressed. Another method is the use of single mode fibers which are extensively applied in high bandwidth applications. Alternatively, the internal profile of the fibers can be modified to create a graded refractive index [64]. The remaining mode dispersion which is not compensated by the graded index profile is called profile dispersion.
Another important factor is the launching condition. If a light pulse is launched, equally distributed in all modes, it will have maximal dispersion. But if only the lowest mode is used and mode coupling is limited, the dispersion will be much less [64]. The mode distribution and the launching conditions (usually expressed in NA values) will therefore not only have a big influence on the attenuation, but also on the bandwidth properties.

2.3.2.2 Chromatic Dispersion

The second most important cause of pulse broadening is chromatic dispersion, also called spectral dispersion. A light pulse always has a certain spectral width and therefore a distribution of several wavelengths. These different wavelengths have slightly different refractive index values, and therefore different propagation speeds inside a medium. As a result, a pulse will broaden when propagating through a fiber. The chromatic dispersion is essentially due to two contributions: material dispersion and waveguide dispersion.

Material dispersion

This dispersion originates from the wavelength dependence on the refractive index [65]. Although this dependence is small, it cannot be neglected for long plastic fibers. Especially in single mode fibers in which there is no mode dispersion present, it will be the major limiting dispersion factor. The material dispersion can be calculated with the following expression [65],

$$D_{Material} = \frac{1}{c}\frac{dn_{2g}(\lambda)}{d\lambda} \approx \frac{1}{c}\frac{dn_{1g}(\lambda)}{d\lambda} \qquad (2.5)$$

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

Waveguide dispersion

Waveguide dispersion is caused by the fact that light waves penetrate the fiber cladding to various depths, depending on the wavelength of the light wave [66]. 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 [64,65].

$$D_{Wg} = -\frac{2\pi\Delta}{\lambda^2}\left(\frac{n^2{}_{2g}}{n_2\omega}\frac{Vd^2(Vb)}{dV^2} + \frac{dn_{2g}}{d\omega}\frac{d(Vb)}{dV}\right) \quad (2.6)$$

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 is the frequency.

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 1550 nm wavelength [66]. 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.

2.4 Standardization of POF

SI-POF is standardized by the International Electrotechnical Commission (IEC) as the A4 category of fibers [30]. 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 standard. Optical Fiber by Performance Standard (OFS) and Nexans have proposed to modify the A4 family of standards to include perfluorinated GI-POF, Table 2.1. According to this proposal, four new fiber families (A4e-A4h) are added to the A4 category [66, 67]. 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. This group has been working in a new commercial standard that would help the POF home/office networking market to develop.

	A4e	A4f	A4g	A4h
Principal applications	Consumer electronics	mobile Industrial	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 2.1: Nexans proposal with 4 new types of perfluorinated GI-POF [66, 67].

2.5 Summary

A brief introduction of the optical fibers in general with its especial emphasis on polymer optical fibers is presented in this chapter. The history of plastic optical fiber (POF) is presented and the different polymer optical fibers are summarized. The optical properties of the POF are shown and its importance for home network application is explained. As a result, one can conclude the PF-GI-POFs are an interesting solution for short reach home networks application.

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3 Chapter 3 Baseband Transmission over POFs

3.1 Introduction

Nowadays, the possibility of the fiber to the home (FTTH) for simultaneous transmission of different services such as internet, telephone, digital television is a reality [1]. However, to meet the more demanding expectations of the end user with new developments, such as video on demand, 4K High Definition (HD) and Three-Dimension (3D) television (TV), cloud computing, video conferences, etc., it is necessary to improve the physical infrastructure of the existing in-home networks in order to obtain the best ratio between quality of service and price of implementation [3, 4]. So, the demand for optical devices that process information at a reduced cost and are easy to install is increasing [2-5].

The main constraint on in-home networking is the requirement for cost-effective installation and user-friendly solutions. The POF shows a user-friendly solution; they are easy to plug, to cut, and to be installed (Do it By Yourself solutions). Regarding the economic aspects of the home networks, the Operational Expenditure (OpEx) and the Capital Expenditure (CapEx) studies were carried out in [6, 7, and 8]. The result shows the potential of the plastic optical fiber in comparison to the other transmission media (CAT-5, SMF, multimode fiber (MMF)) in network topologies point to point (P2P) and point-to-multipoint (P2MP). For a typical residential home (M=3 floors and N=4 rooms/floor), the installation cost (CapEx) in the plastic optical fiber is a cost competitive solution, in comparison with the SMF and MMF, because of the easy connectorization of the large core POFs[6]. The CapEX advantage can be further increased, when the cost of the media convertor is decreased (as expected, the market of the POF will become more mature) [7]. Regarding the operational cost OPEX, the CAT technology consumes lower power than the others (SMF, MMF and POF) since they do not need electrical and optical convertors. Therefore, the large core POF is a strong candidate, providing the potential for simpler installation, reduced operational complexity, and, hence, reducing cost [1, 8]. The large core POF provides an acceptable bandwidth with the potential for do-it-yourself installation. This chapter focuses on visibility of the plastic optical fiber in home area network. Section 3.2 outlines different types of the commercially available POFs with their optical and physical characteristics. The plastic optical fiber link and devices are introduced in this section as well. Section 3.3 presents the experimental and numerical results, regarding the transmission performance of the point to point link over the POFs. Finally, the main conclusions of the chapter are summarized in Section 3.4.

3.2 POF data link and system devices

The general schematic of the point to point (P2P) transmission link based on the plastic optical fiber is shown in Fig.3.1.

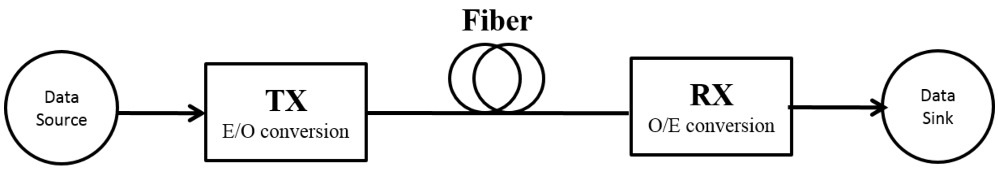


Figure 3.1: Basic optical fibre system block diagram

A common optical system consists of a data source which provides an electrical signal, a transmitter for the electro-optical conversion, a transmission media (optical fiber), a receiver for the optical to electrical conversion, and a data sink. Typically, the optical transmission in a fiber is unidirectional. Thus, a bidirectional communication requires a pair of fibers (two fibers). On the transmission side (TX), electrical optical conversion is done by light sources; i.e., light emitting diode (LED) or a laser diode. The light coupled to the fiber is done with simple plastic lenses or even without coupling optics. The plastic fiber, itself, is connected to the active components either with simple plastic connectors or even without connectors. On the receiver side (RX), a photo diode makes the optical electrical conversion to recover the transmitted signal. In a short-reach multimode optical communication system, like the home access networks, direct intensity modulation and direct detection (IM/DD) is typically used, instead of coherent detection, due to its cost, latency, and low power constraints [8]. In a directly modulated system, on transmission side, only the intensity of the light is modulated, and phase modulation is not required for such system. On the receiver side, only the intensity of the light must be detected; therefore, a simple photo diode is enough to capture all the received signals. In this section, different types of the POFs and optical source and receivers are presented.

3.2.1 Polymer optical fibres

Polymer optical fibers [10] are made of plastic, which is a very tolerant material in terms of stress and handling in comparison with the silica fiber. Among the polymer materials, poly-methyl-methacrylate (PMMA) is the most popular and widely used material. The large core POFs (usually with 1 mm core size) show great advantages, such as easy installation and low-cost solutions in home area network, as discussed in the previous section. However, the large core diameter and the large numerical aperture (NA) have to be at the expense with a small bandwidth due to large modal dispersion, and a high attenuation due to multiple internal reflections [11, 7]. The three most common POFs are the step-index poly-methyl-methacrylate (PMMA) based POF (SI-POF), the graded index PMMA-based POF (GI-POF), both with a core diameter of about 1 mm, and the graded-index perfluorinated POF (PF-GI-POF) with core diameters varying from 50, 62.5 µm to up to 120 µm. Table 3.1 summarizes the properties of all the aforementioned fiber types in terms of material, core diameter, numerical aperture (NA), transmission wavelength range, modal bandwidth-length product, and typical application scenarios. The SI-POF and the GI-POF are the most widely used fibers for data communication, which are made of PMMA. These fibers work in a visible wavelength range, especially in red, green and blue window. All other fibers have their attenuation minimum in the near-infrared wavelength range at 850, 1310 or 1550 nm.

	SI-POF	GI-POF	PF-GI-POF	MMF	SSMF
Material	PMMA	PMMA	Cytop	Silica	Silica
Core diameter	1 mm	1 mm	50-120µm	50/62.5 µm	9 µm
NA	0.5	0.23	0.18	0.2	0.12
Wavelength range	400-650nm	650nm	850/1310nm	850/1310nm	1310/1550nm
Attenuation	< 160 dB/km	< 200 dB/km	< 50 dB/km	< 3 dB/km	< 0.2 dB/km
Modal bandwidth	5 MHz.km	>150 MHz.km	>3 GHz.km	>3.5 GHz.km	Not applicable
Application scenario	Automovie Home networks	Home networks HDMI(HDTV)	Enterprise Interconnect Home networks	Home networks Radio over fibre	Long Haul Metro Access networks

Table 3.1: Key parameter comparison of optical fibers based on polymer and silica [12].

It is clear from the table that the PF-GI-POF has lower attenuation due to the material amorphous perfluorinated polymer, and was developed by Asahi Glass in Japan [13]. The core sizes of this fiber type are comparable to the silica based MMFs; thus, the big advantage is that the optical component developed for MMF can be used. The SI-POF is the worst fiber type in terms of the bandwidth with a modal bandwidth-length product of 5 MHz· km. But, because of its low price, high tolerance, and easy to use, it is the mostly used POF in very short reach applications such as automobiles [14, 15]. On the other hand, the graded index PMMA-based POF has a higher bandwidth; yet, this has to be paid with a much higher attenuation and a smaller NA, which makes the coupling between a light source and the fiber core more complicated. At the moment, due to some technical issues such as temperature stability and purity of the material, this fiber is not yet available as a standard product [15]. However, if these problems can be solved, this type of POF will be very promising candidate for next generation high speed (Gigabit range) POF based data transmission systems in home networks.

3.2.2 Optical transmitters for POF systems

The choice of the light source in the POF based systems is strongly dependent on the environmental requirements of the transmission system and on the required data speed [16, 17]. The simplest and oldest type of a light source for the POF systems is light emitting diode (LED). Because of the large NA (0.8) and its robustness, 650nm LEDs are one of the most often used light sources for the POF systems, where the low loss region of the PMMA based POF is also around 650nm[18]. The main advantages of the LEDs are their low cost, long life time, and operating in a wide temperature range. On the other hand, they have a small bandwidth which limits their applications to very low speed transmission systems like automovie applications [19]. Recent developments in LED technologies have resulted in 650 nm Resonant-Cavity LEDs (RC- LED) which improve the modulation bandwidth but, on the other hand, introduce a smaller launching beam (NA=0.34). The typical parameters of the red RC-LED are summarized in table 3.3. The best light source in terms of output power and modulation bandwidth is a laser diode. In the red wavelength window, edge-emitting laser diodes are available, originally designed for DVD players [20]. The maximum peak output power is approximately +7 dBm and the modulation bandwidth is higher than 2 GHz. Furthermore, laser with its small operating temperature is very expensive in comparison to a LED, and the driving current has to be adapted to the temperature of the component since the output power of a laser diode is strongly sensitive to the temperature [18-20]. The only suitable application scenario is the consumer electronics market [21]. An alternative to the edge emitting laser diode is the use of a vertical cavity surface emitting laser diode (VCSEL). This vertical structure can be produced in a much cheaper process, but the temperature range for these devices remains the same as for a laser diode [22]. An advantage is that the threshold current of a VCSEL to get into the lasting effect region is much lower; thus, the driving current is much smaller, as it can be seen in Table 3.3. Moreover, VCSELs offer simplicity, high power at low current drive, ease of coupling, good spectral characteristics, high bandwidth (~ 5 GHz now), and LOW COST! [22]. To summarize, a red LED or a RC-LED is the preferred optical light source for short-reach POF systems which are not designed for large bandwidth and speed, such as car applications [20].

	LED	RC-LED	Edge-emitting LD	VCSEL
Typical Wavelength	650nm	650nm	1310-1550nm	850nm
Spectral width	25 nm	20 nm	1 nm	1 nm
Launch NA	0.8	0.34	0.13	0.23
Temperature range (operation)	-40^0C . . 95^0C	-40^0C . . 95^0C	-10^0C . . 60^0C	0^0C . . 40^0C
Threshold Current	n/a	n/a	20 to 50 mA	Medium
Date rate	100 Mb/s	200 Mb/s	> Gb/s	> Gb/s
Optical bandwidth	80 MHz	100 MHz	> 2 GHz	> 2 GHz
Packaging cost	Low	Low	High	Low
Compatible optical fibre	POF	POF	SM Fibre	MM Fiber PF-GI POF Fiber

Table 3.2: Key parameter comparison of optical light sources for polymer optical fiber systems [22]

Alternatively, the laser diode, especially VCSEL, is a promising solution for >1 Gb/s and analog applications, thanks to its broad bandwidth and good linearity. VCSEls are widely used on the PF-GI-POF because of their optimized properties in 850nm wavelength, where these types of the plastic fibers have their minimum attenuation window [23].

3.2.3 Optical receivers

Optical receivers used for the POF systems include PIN photodiodes and avalanche photodiodes (APD). The PIN diode is the simplest and the most common device for fiber optics systems. The main advantages of the PINs are their low-cost, being easy to use, and their relatively fast response time [24]. Their active area is usually large enough to match the large numerical aperture of the POF. Their larger photo sensitivity area makes fibre-to-photo diode alignment easier, but results in a narrower bandwidth, which is a critical factor for high capacity POF transmission systems [25]. The responsivity of the PIN diodes varies with wavelength and materials, but usually ranges from 0.4 to 0.9 A/W [24]. This low responsivity requires trans-impedance amplifiers (TIAs) to have a sufficient output power. Compared to the PINs, the APDs provide much higher gain and are more sensitive to low-power signals. An additional advantage of the APDs is that they work very fast, turning on and off much faster than a PIN diode [24]. The drawback of the APD is that it requires a high voltage for operation and is sensitive to variations in temperature. In addition, the noise level of the APD is generally higher than the PIN due to its internal stochastic multiplication gain [26]. Therefore, when the input signal is relatively low, the PIN+TIA are preferred above the APD and post amplifiers. However, when sufficient input power is available and speed is required, APD-based receivers are the preferred choice.

3.2.4 Modulation Formats

The main limitation of the POFs is modal dispersion as discussed in previous section. Dispersion limits the bandwidth of SI-POF to approximately 10 MHz.km or 10 GHz.m. Several techniques have been proposed to increase the data rate of the POF systems both in electrical and optical domains. In the electrical domain, modulation and equalization techniques, such as multilevel pulse amplitude modulation (M-PAM), multicarrier modulation, as well as fixed and adaptive equalization, have been developed. In the optical domain, special filtering techniques, such as restricted mode launching and photo detectors with small active area, have been proposed [22, 27]. This subchapter reviews some of the techniques that have been proposed in an attempt to increase the speed of POF links. A suitable selection of applied modulation formats is an important factor for fiber-based transmission systems. The main issue that should be taken into account in using different modulation format and /or equalization techniques in the plastic optical fiber systems is the system complexity and cost.

Non-return-to-zero (NRZ): This modulation scheme is also known as on-off keying (OOK). NRZ is the simplest and oldest modulation format but with a low spectral efficiency (1 bit/Hz) m. Commercially available optical components on the market use this modulation format for IM/DD systems. In the NRZ modulation scheme, the signal has two possible amplitude levels or symbols, "1" or "0". Thus, each symbol transmits only one bit. In this modulation, only two bits have to be generated; hence, the design of the transmitter and the receiver is quite easy and simple. The maximum length and data rate of the POFs when using NRZ modulation is limited due to the strong modal dispersion in the large core POFs. Accordingly, more spectral/power efficient modulation schemes than NRZ is required to obtain a higher capacity and longer reach [28] Multi-level modulations always considered as a main alternative, but we have to concern with their complexity and power budget as well. In this thesis, the use of multilevel modulation is proposed to reduce the required symbol rates, because of the severe inter-symbol interference (ISI) induced by the transmitter and the POF channel.

Pulse amplitude modulation (PAM): PAM is a simple multi-level modulation scheme, where the message information is encoded in the amplitude of a series of signal pulses. The PAM modulation encodes $\log_2(M)$ bits of information into one symbol [28]. So, $\log_2(M)$ bits are mapped on one PAM-M symbol of the alphabet {±1,±3, . . . ,±(M−1)}. The benefit of using PAM is that the symbol rate for a constant bit rate is reduced by a factor of $\log_2(M)$ and thus the required receiver bandwidth is divided by this factor also, which leads to less noise at the receiver. In case of 4-level pulse amplitude modulation (4-PAM), this means half of the bandwidth in comparison to the simple NRZ modulation. Thus, the electrical noise bandwidth is reduced by a factor of two, or 3 dB in the electrical domain, which translate into 1.5 dB in the optical domain. The drawback of the PAM-M is that the receiver must detect M different levels, which results complexity in the receiver side of the system. Theoretically, the bandwidth required to transmit the signal can be further reduced by increasing the number of bits per symbol, thereby reducing the baud rate. However, this requires additional power at the transmitter to resolve the multilevel signals and increases the bit error rate (BER) on the receiver side due to noise. The optical power penalty for the PAM modulation, compared to the NRZ modulation, at same symbol rate is [28]:

$$P_{ps} = 10\log_{10}(M-1) \quad (3.1)$$

Where, M is number of the PAM level. It means 4.8 dB more received optical power is needed for the 4-PAM modulation at a same symbol rate as the NRZ. The power penalty at the same bit-rate is [28]:

$$P_{pb} = 10\log_{10}\left(\frac{M-1}{\sqrt{\log_2(M)}}\right) \quad (3.2)$$

Where, M is number of the PAM level. For the 4-PAM this gives that 3.3 dB more optical power is required compared to the OOK signal at the same bit-rate to reach the same bit error rate (BER). Nevertheless, the use of PAM-4 has some advantages. For example, the decreased symbol rate leads to a slower signal processing clock if digital signal processing is used. Further information related to the PAM modulation can be find in [28-30].

The PAM-4 modulation has been extensively studied over the plastic optical fibers by different groups in recent years [30-34]. The PAM modulation offers some advantages such as a simple design in transmission side and better sensitivity in terms of optical received power. On the other hand, their receiver design, in comparison to the NRZ modulation, is more complex since it has to detect M different levels each time.

Other advanced and spectrally efficient modulations schemes like Carrierless amplitude phase modulation (CAP) [36] or DMT (Discrete MultiTone) [37] are also considered as a solution for short-reach optical application scenarios. There have been numerous successful demonstrations of such modulation over the plastic optical fiber, presented in the literature [36-40]. For example, 2 Gbit/s in a 100 m SI POF was achieved by using CAP modulation in combination with digital equalization [38]. The main limitation associated with these modulations, in comparison to the PAM modulation, is the signal processing complexity of the end systems owing to the complicated multiplexing and de-multiplexing process. Another disadvantage of the subcarrier schemes, compared to PAM, is worse sensitivity, in terms of optical received power [27, 36 and 40], and also the BER is quite high compared to the multilevel signalling technique. Moreover, the link cost is still not reasonable for short-reach network applications in home networks [40].

3.2.5 Equalization schemes

Equalization is a very popular technique which is often employed to mitigate the effects of inter symbol interference (ISI) in transmission media such as wireless or the POF systems [41]. The bandwidth limitation of the POF systems, due to the modal dispersion or due to bandwidth limited transmitter components, can be compensated by using the electrical equalizations. Two main equalization techniques are widely used in the POF systems. The first one is known as feed-forward equalizer (FFE). A linear FFE [42] is the simplest structure and the most cost-effective solution. It consists of a delay line filter or finite impulse response (FIR) filter with filter coefficients that are adaptively adjusted to the channel impairments [42]. The equalizer coefficients can be calculated in an optimal way solving the Wiener-Hopf equations [42, 43], also known as the Minimum Mean Square Error method (MMSE). A more advance equalizer is the decision feedback equalizer (DFE). The DFE makes use of the previous decisions in attempting to estimate the current symbol [21]. Any “trailing” intersymbol interference caused by the previous symbols is reconstructed and then subtracted [43]. A typical DFE consists of a feed forward filter, a non-linear feedback filter, and a decision device [43]. The feed-forward filter is used to minimize the ISI induced by future symbols (pre-cursors). The nonlinear feedback equalizer adjusts the input level to the decision device symbol by symbol based on known past symbols (post-cursors). Thus, a DFE can remove ISI from the past symbols without any noise amplification. For detailed information about these equalization schemes, it is referred to the literature [42-46].

3.3 Transmissions performances over plastic optical fiber

3.3.1 An overview of the transmission over large core POFs

A large number of studies, presented in the literature, focus on the transmission over step index plastic optical fiber. Research on high-capacity POF links was the topic of European project POF ALL and POF-PLUS in last few years [47, 48]. The results of their big efforts to achieve maximum throughput and link length over large core SI-POFs are presented in different journal, conference papers, and some PhD theses [15, 21, 26 and 46-49]. For example, real-time PAM-2 experiments have been reported at 1.25 Gb/s over 75 m of the SI-POF using DFE [49] and a 10.7 Gb/s over shorter POF lengths (15 m 1 mm core SI-POF using FFE and DFE[50], and 35 m 1 mm core GI-POF using MLSE) [51]. By using PAM-4 modulation scheme, 10.7 Gb/s was carried over 25 m of the SI-POF and 60 m of the GI-POF using DFE [52]. An overview of multi-Gb/s system experiments using 1mm core POF is given in Table 3.3. The experimental trials reported in this table have demonstrated the feasibility of POF links for high capacity transmissions. These trials represent record achievements in data transmission over the PMMA-POF and are in chronological order. This summary is, not complete; however, it highlights milestone results and clearly shows the improvements in achieved transmission capacity and link distances. From the results in Table 3.3, one can clearly see how the POF technology has evolved, over the past few years to its current state supporting high capacity data-rate transmission. The maximum throughput achieved was 10.7 Gbps over 30m of the SI-POF using a complex modulation and heavy algorithm for receiver equalization.

Data rate	POF type	TX	Wavelength	RX	Format	Length	**Ref.**
100Mbps	SI-POF	LED	520nm	APD	8-PAM	250m	[53]
1.25 Gb/s	SI-POF	Eye safe RC-LED	650nm	Large area Receiver	OOK	50m	[54]
10 Gb/s	SI-POF	High power laser	650nm	APD	DMT	25m	[55]
10.7Gb/s	SI-POF	WDM high power laser	405,515 and 650nm	PIN+TIA	DMT	50m	[56]
3Gb/s wired+480Mbps wireless	GI-POF	VCSEL	665nm	APD	DMT/OFDM	50m	[57]
5.3 Gb/s	GI-POF	Eye safe-VCSEL	665nm	PIN+TIA	DMT	10m	[58]
5.8Gb/s	GI-POF	High power laser	650nm	PIN+TIA	PAM-2+DFE	75m	[59]
10.7Gb/s	GI-POF	VCSEL	850nm	PIN+TIA	DMT	35m	[60]
47.4 Gb/s	GI-POF	DFB laser	1300nm	Multimode fiber-coupled photodetector	DMT	100m	[61]
112Gb/s	GI-POF	External cavity laser (ECL)	1550.52nm)	Digital coherent detection	Quadrature phase shift keying (QPSK)	100m	[62]

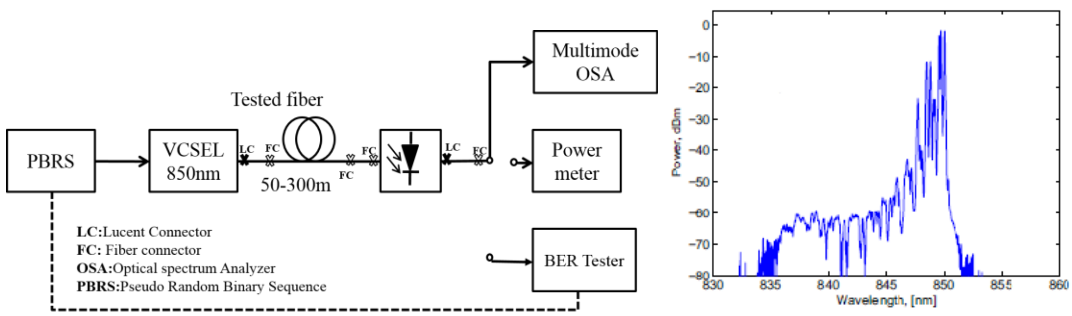
Table 3.3: Multi Gb/s system experiments (Using SI/GI-POFs)

3.3.2 Transmission performances over PF-GI-POF (Experimental Study)

In comparison to multimode silica fibers or PMMA SI-POFs, the perfluorinated graded-index polymer optical fiber (PF-GI-POF) with core diameters of 50 µm, 62.5 µm, or 120 µm is a promising alternative due to its ease of use and installation with clip-on connectors requiring minimal training [21]. It is also shown [63,64] that the PF-GI-POFs are compatible to the low cost and low power consumption vertical cavity surface emitting lasers (VCSELs) at 850nm wavelength, where these types of fiber have their minimum attenuation in this region. In this section, high data rate links using GI-PF-POFs are demonstrated. The link lengths are limited because of the bandwidth limitation due to the modal dispersion in multimode fiber. Thus, one of the primary objectives of the research was to improve knowledge of multimode optical transmission over the PF-GI-POFs with core diameter of 50 µm. The first experimental study reveals the visibility of using the NRZ modulation with commercially available optical components [64]. Also, a simulation study was carried out, comparing the transmission performance of the NRZ modulation with PAM-4 modulation in combination with the receiver equalizers. Two studies are presented enabling 10 Gbit/s transmissions over up to 300 m of the PF-GI-POF.

3.3.2.1 Experimental Setup

The main goal of this experiment was to study the multimode transmission over commercially available PF-GI-POF with 50 μm core. The optical performance of the multimode transmission such as bit error rate (BER) with different length of the fiber over a range of the bit rates (up to 10Gbps), as well as the commercially available components regarding our implementation, is also discussed in this subchapter. The used components are low cost and have simply connectorized. Fig.3.3 (a) shows the experimental setup of the point to point transmission link, for measuring the BER and optical losses of the tested fiber. On the transceiver side of the setup, a commercially available multimode fiber-pigtailed Vertical-Cavity Surface-Emitting Laser (VCSEL) with an operating wavelength of 850 nm is used.



(a) (b)

Figure 3.2: Configuration of the circuit to test the BER and Losses (a): Measured optical spectrum of VCSEL(FTLX8571D3BC) used in transmission experiment with 0.05 nm resolution bandwidth (b).

Commercially available VCSELs are optimized for different data rates. In this experiment, two VCSELs were used: commercially available 850nm low cost XFP transceivers FTLF8524P2BNV with maximum output power of –6.8 dBm [65] operating up to 4.25 Gbps and FTLX8571D3BC [66] with maximum average power of -3.3 dBm which supports the higher throughput up to 10Gbps. The generated NRZ electrical date by a signal generator (Agilent, 86I00A) with carrier frequencies between 100 MHz and 3.2 GHz were directly fed to the VCSELs. The Agilent 86100 wide band spectrum is used to evaluate the eye diagrams of the received signal. The tested plastic optical fiber was with NA = 0.19 and bending radius of the 5 mm. The tested fiber (300m length) is directly connected by multimode FC/PC connectors to the photo detector. A fiber adaptor is used to change the offset position between the fibers. After transmission, the optical power profile and the bit error ratio of the transmitted signal were measured using an optical spectrum analyzer (OSA) (YOKOGAVA, AQ63738) and BER analyzer, respectively. In order to evaluate the transmission performance, the transmitted signal was converted into an electrical one by a photodetector mounted in a similar evaluation board as the VCSEL [65] with a maximum sensitivity of -22 dBm and -18 dBm for lower and higher data rates, respectively.

3.3.2 Experimental results and discussion

A preliminary study dealing with lower data rate (1.25 Gbps) has been performed according to the Gigabit Ethernet standard (GbE). The transmission has been demonstrated through the large core diameter fiber at 850 nm (length: 50 m up to 300 m with span of 50m). The optical received power measured for back to back (B2B) was -8.3dBm. The eye diagram of the link with data rate of 1.25 Gb/s over 200m and 2.5 Gb/s over 100m is shown in Fig 3.3 a and b, respectively.

(a) (b)

Figure 3.3: Eye diagram of the 1.25 Gbps over 200m of fiber (a) and Eye diagram of the 2.5 Gbps transmission over 100 m (b)

The experimental study also shows as the length of the fiber increases, the optical losses follow the same tendency. Base band data of the 1.25 Gbps can reach to the long distance of 150 m with losses lower than -22 dBm, while the 10 Gbps data losses reach the threshold of the receiver's sensitivity at 100 m with -18dBm. The size and potential transmission data rates over the PF-GI-POF with a core diameter of 50µm was measured. The BER and the received optical loss measurements indicate that we can build a point to point link with this optical fiber, with maximum distance of the 200 m for 2.5 Gbps and 50 m for 10 Gbps with BER lower than 10^{-3}. Maximum lengths increase is possible but requires transceivers with high power optical signal and/or using highly sensitive photo detectors. Also, using a multilevel modulation instead of a simple NRZ modulation and/or using electrical equalization may improve it. In the next subchapter, the transmission performance of the PF-GI-POF, by using a receiver equalization, is presented.

3.4 Comparison of NRZ and PAM-4 for 10 Gbit/s over PF-GI-POF

The goal of this simulation study is to make a comparison between the NRZ and the PAM-4 modulation for 10 Gbit/s transmissions over 300 m PF-GI-POF.

3.4.1 Simulation setup

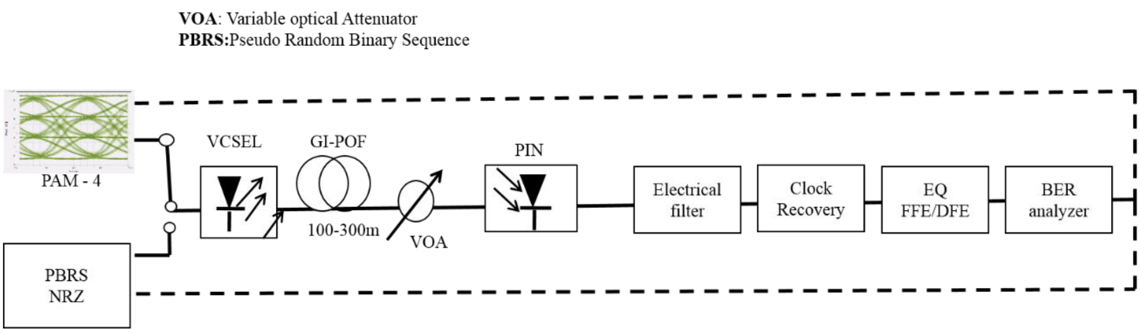


Figure 3.4: General simulation setup for comparing the simple NRZ modulation to Multilevel PAM-4 modulation

For the simulation study, the VPI transmissionMaker software was applied for modelling optical system and sub-systems for the work presented here. The simulation setup is shown in Fig3.4. A bit pattern generator is used to generate the PAM-4 (symbol rate of 5 GSymbol/s and a bit-rate of 10 Gbit/s) and the NRZ electrical signal. The pseudo random binary sequence (PRBS) used for 10 Gb/s data was PRBS7 ($2^7 - 1$). For electro-optical conversion, a directly-modulated commercial 850 nm multimode vertical cavity surface emitting laser (VCSEL) with an average output power of -8.3 dBm is used. This optical signal is launched into different lengths (100-300m) of the perfluorinated graded-index polymer optical fiber (PF-GI-POF), which is a commercially available fiber with a core diameter of 50 µm and a total diameter of 500 µm including cladding. The attenuation is approximately 40 dB/km at 850 nm and the numerical aperture (NA) is 0.185. The PIN photodiode was modelled with a responsivity equal to 0.6 A/W and without any thermal noise. The default receiver electrical filter was a 7 GHz Bessel 4th-order function. After the clock recovery, the signal is fed into the feed-forward (FFE) or the decision-feedback equalizer (DFE). At the end, the equalized sequence is demodulated and compared with the transmitted bit sequence to get the BER.

3.4.2 Simulation Results and Discussions

The bit-error ratio (BER) performance simulations, approximately 10 million bits, are transmitted, and the length of the GI-POFs varied from 50-300m with the span of 50m each. In order to get the optimum number of required equalizer taps, the BER measurement was done for different numbers of filter taps for both FFE and DFE equalizers. The simulation result and also the experiment validation [57] show that the minimum required equalizer tap is 7 tap for FFE and 5 forward and 3 feedback taps for DFE (5, 3) for a sufficient result. In this simulation, we employed 13 taps for FFE and DFE with 12 forward and 7 feedback taps (DFE (12, 7)).

3.4.2.1 Results with NRZ modulation

The effects of the number of the tap coefficients in different length of the GI-POF, while using NRZ modulation is shown in Fig.3.5. Simulation study shows if no feedback taps (13FFE) are used, the maximum transmission length with NRZ modulation for BER lower than 10E-3 was 150m. However, results are improved when the combination of the feedback and forward taps is used. The best result obtained by combination of the two equalizers with 12 forward and 7 feedback taps of the DFE with maximum reach of the 300m. The performance improvement due to equalization for 10 Gbit/s transmissions is further investigated by measuring the BER at a variable received optical power for different lengths of the GI-POFs. In this scenario, the variable optical attenuator is placed at the link before signal into receiver to adjust the optical power received in Fig.3.4 configuration.

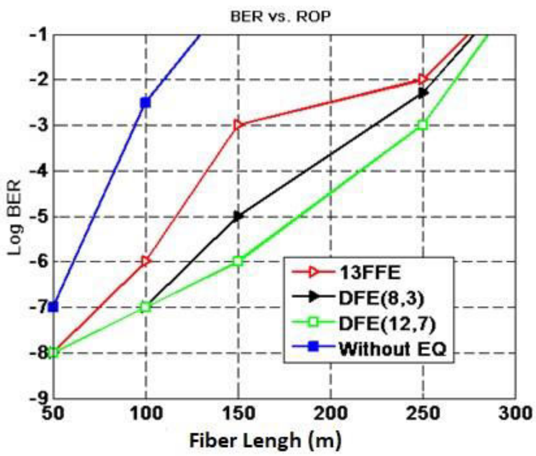


Figure 3.5 : BER versus received optical power in NRZ modulation for different number of the equalization taps

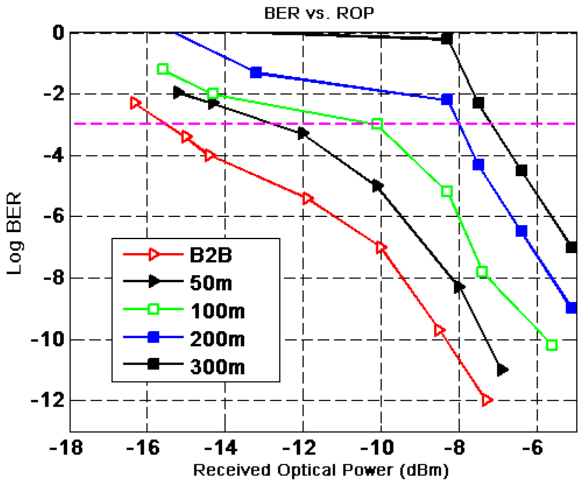


Figure 3.6: BER vs average received optical power for NRZ modulation at 10 Gbps

BER versus optical power received for different length of the GI-POF at 10Gbps with NRZ-DFE is presented in Fig3. 6. Clearly can be seen at lower length of the GI-POFs fiber, measured points follow better the fit lines. It is probably due to the optimization of the decision point was more difficult at longer length with larger dispersion effects.

The eye diagram of 200m length fiber before and after the DFE equalization is shown in Fig.3.7. At a fiber length of 200 m, the equalized eye for the NRZ is clearly open and no error can be counted within the transmitted bits.

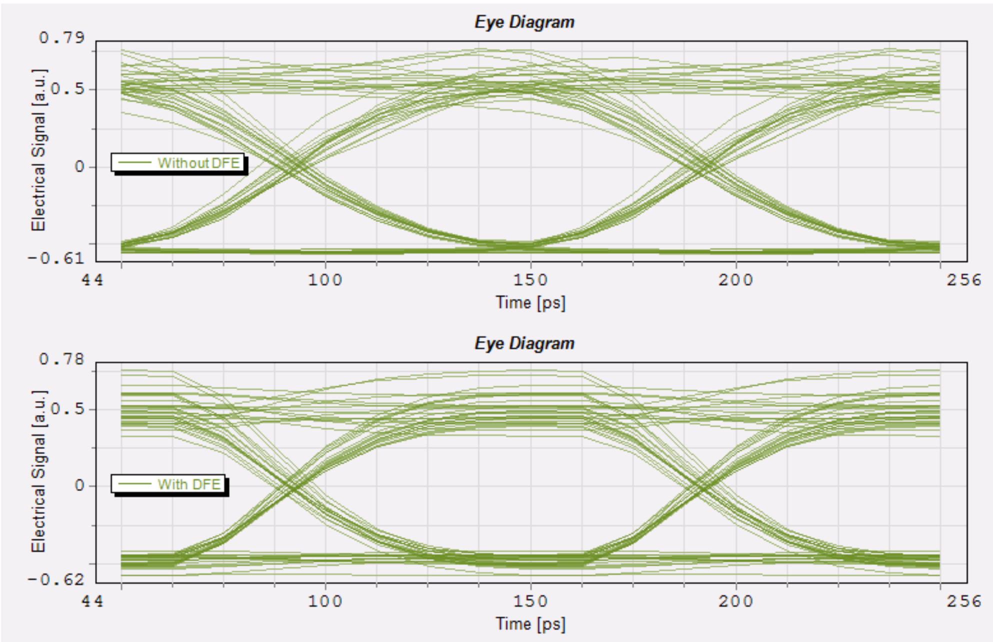


Figure 3.7: Eye diagram before and after equalization (DFE 12, 7) for fiber lengths of 200 m.

3.4.2.2 Results with PAM modulation

The simulation study when using the PAM-4 modulation in combination with different equalizers is presented in Fig.3.8. The simulation result shows with PAM-4 modulation. The maximum reach with DFE+FFE equalizer increased to 300m while for only FFE

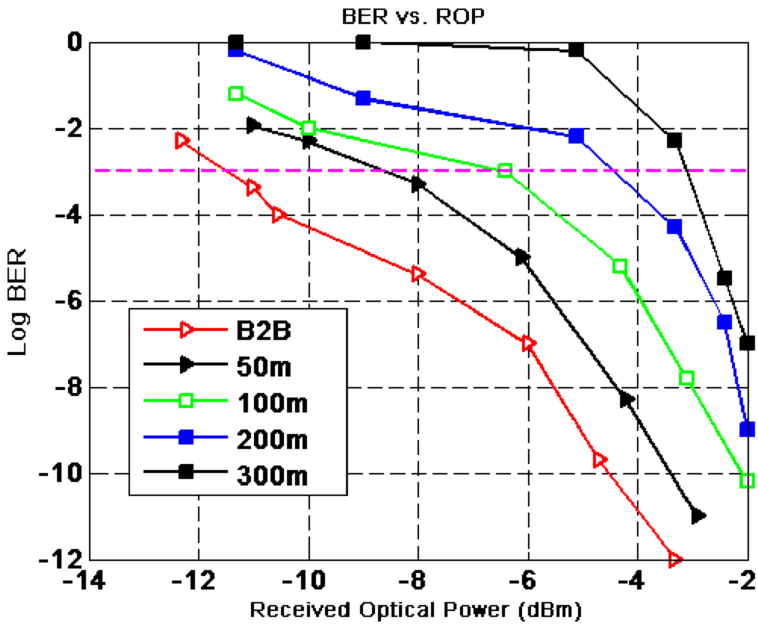


Figure 3.8: BER vs average received optical fiber for 4-PAM at 10 Gbps.

used is about 200m.

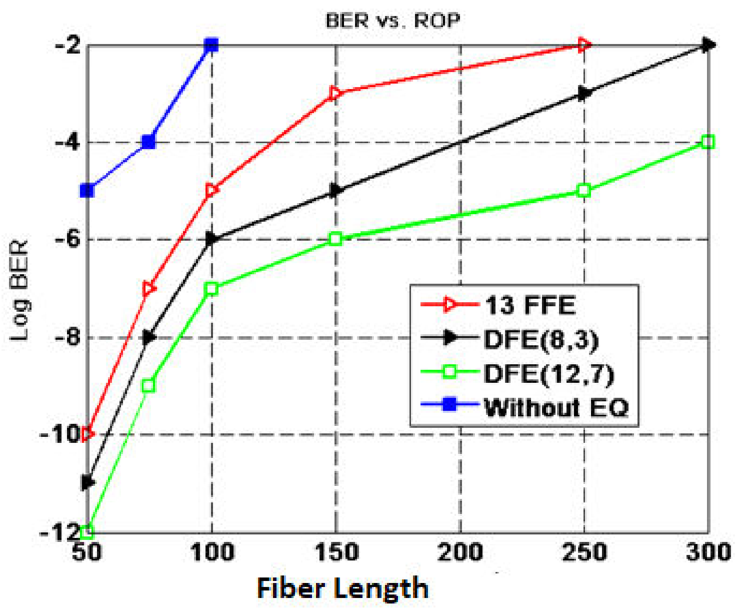
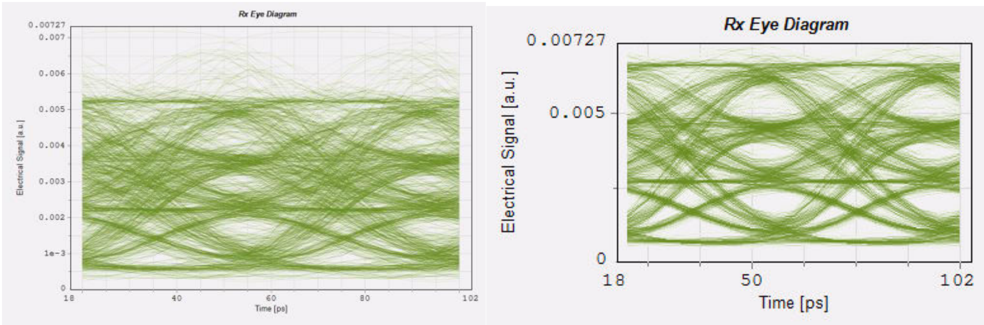


Figure 3.9: BER versus received optical power in 4-PAM modulation for different number of the equalization taps

BER vs average received optical fiber for 4-PAM at same bit rate as NRZ modulation is measured. In this scenario, the variable optical attenuator placed at the link before the signal into receiver to adjust the optical power received in Fig.3.4 configuration . The BER versus the optical power received for different length of the GI-POF at 10Gbps with the PAM-4 DFE (12, 7) is presented in Fig3. 9. The eye diagram of 200m length of the fiber with the PAM modulation in combination with the DFE equalizer is shown in Fig3.10.



(a) (b)

Figure 3.10: Eye diagrams before (a) and after equalization (DFE 12, 7) (b) over 100m of the PF- GI-POF

3.4.2.3 Discussion

The results of the two modulations with equalization can be explained as following: since the dispersion effect in multimode plastic optical fibers is very high [60], it is difficult to completely reduce the ISI by just only using FFE equalizer. In DFE implementation, a combination of FFE and feedback equalizer is used to better compensate the effects of inert symbol interference (ISI). Comparing the NRZ and PAM modulation in this study shows, the ISI of the PAM-4 signal can be better compensated than the ISI from NRZ, due to the smaller bandwidth demand of the PAM-4 signal. The simulation result manifests that if no feedback taps (13FFE) are used, the maximum transmission length with the NRZ modulation for BER lower than 1.0E-3 is 150m. However, the results are improved when the combination of the FFE+DFE is used. The best result is obtained by combination of the two equalizers with 12 FFE and 7 taps of the DFE with maximum reach of the 300m. The received power of 4-PAM at 10Gbps was 4.2 dB higher than of NRZ at 10 Gbps, while a 3.3 dB difference was expected from theory [14]. This difference can probably because of the present of the low pass filter (LPF) and was no ideally matched to the received signal. Within the measured received optical fiber both NRZ and PAM-4 modulations could reach up to 300m with BER of the 10E-3, although PAM-4 modulation requires higher received power than NRZ.

3.5 Summary

This chapter briefly overviews the visibility of the optical fibers in-home networks. The current and alternative solutions for in-home networks considering the economic and technical perspectives are presented in Section 3.1. It is clear that the plastic optical fibers (POFs) are the best media for offering a high capacity converged network solution. POF provides advantages of being robust, low-cost and easy-to-install in comparison to the CAT development or multimode silica fibers. Among many types of fibers, the PF-GI-POF offers higher bandwidth, lower attenuation in 850nm wavelength. Moreover, PF-GI-POFs are more compatible to the low cost and low power consumption vertical cavity surface emitting lasers (VCSELs) at 850nm wavelength, where this type of the fiber has their lower attenuation loss in this region. A POF optical transmission system generally consists of the POF link, optical transmitter and optical receiver. The main characteristics of these three components are discussed in Section 3.2 based on the state-of-the-art available products in the market. Section 3.3 mainly focused on the experimental and simulation studies over PF-GI-POF. The experimental study shows that the maximum link length is limited to 100m, while using the simple NRZ modulation at data rate of 10Gb/s. The bandwidth limitation due to the modal dispersion in a PF-GI-POF transmission system can be counteracted by using electrical equalizers and/or using more advanced modulation schemes. As the main cost of the network implementations inside the housed has to pay by the owners, the cost and simplicity are the two main issues to be considered. For the simplicity and easy to use and less power consumption PAM-4 modulation and simple FFE and DFE equalization techniques is used in simulation studies to overcome the bandwidth limitation of the multimode PF-GI-POFs. The simulation results demonstrate that combination of the DFE equalizer with NRZ modulation, transmission length can be increased to 300m long. It has been also shown that with advanced multilevel modulation schemes, short reach home access network can be realized with high spectral efficiencies. We investigated the performance of 10 Gb/s 4-PAM as an alternative modulation format in short-range VCSEL-based point-to-point links. The simulation results show that 4-PAM required significantly more receiver power than NRZ, 4 dB more at the same bit-rate. In short distance application in home network, the performance of the PAM FFE or DFE with advantage of the low complexity and cheap components could be a promising solution for next generation of 10 Gb/s PF-GI-POF systems.

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4 Chapter 4 WDM over POFs

4.1 Introduction

In the previous chapter, the viability of the plastic optical fibers (POFs) in point to point (P2P) link is discussed. After manipulating the capabilities of a single channel, the next step to increase the capacity of the POFs is to use multiple channels over a single fiber which is well known as wavelength division multiplexing (WDM). The WDM technology enables the simultaneous transmission of different signals in the same optical fiber. Although, these techniques have been well studied in glass fibers, this is not the case for polymer fiber. In the WDM technique, different wavelengths which are jointly transmitted over a fiber must be separated to regain all information. An important element in the WDM systems is a fiber Bragg grating (FBG). The FBG is needed to filter and separate the different wavelengths at the receiver side to obtain the signal information. Moreover, Bragg gratings can be used in numerous other applications such as sensors, spectrum analyzers and fiber lasers [1, 2]. In this chapter, first in section 4.2, the basic FBG theory is explained followed by a review of the history of fiber Bragg gratings in polymer optical fibers. The application of the FBG as a filter in WDM system over plastic optical fiber to increase the capacity of the POF link is discussed in section 4.3. The simulation study to increase the optical capacity of the POFs is discussed in section 4.4. Finally, the main conclusions of the chapter are summarized in Section 4.5.

4.2 Fiber Bragg gratings (FBG)

A fiber Bragg grating (FBG) is a piece of optical fiber which consist of a periodic variation of the refractive index in the core of an optical fiber [1]. It acts like a band-rejection filter, reflecting wavelengths that satisfy the Bragg condition λ_{Bragg} and transmitting the others. If a broadband light spectrum is coupled into a fiber containing an FBG, a portion of the incident spectrum is reflected according to the specifications of the FBG, whereas the other part is transmitted [1, 3]. Fig 4.1 shows the basic principle of the Bragg grating in optical fiber. The equation relating the grating periodicity and the Bragg wavelength depends on the effective refractive index of the transmitting medium, n_{eff}, and is given by [2]

$$\lambda_{Bragg} = 2n_{eff}.\Lambda \qquad (4.1)$$

Where, λ_{Bragg} is the Bragg Wavelength, Λ is the Grating period and n_{eff} is effective refractive index of the fiber core. Figure 4.2 also shows the application of a FBG as a filter in a typical optical communication.

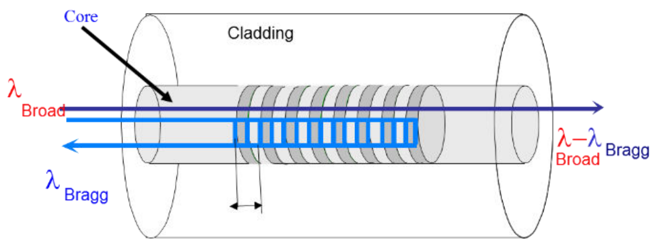

Figure 4.1: Schematic representation of a fibre Bragg grating

Light waves at several different wavelengths are traveling through the optical fiber and entering into the FBG. One of the wavelengths ($\lambda_1 = \lambda_{Bragg}$) is reflected back by the FBG which comes back to the circulator. The circulator separates the Bragg wavelength from the incoming wavelengths and the reflection spectrum of this reflected wavelength can be seen on an optical spectrum analyzer.

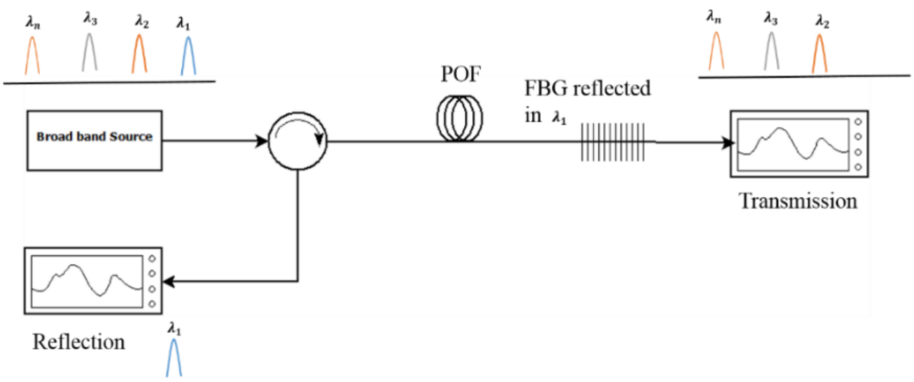

Figure 4.2: Measurement setup for Grating reflection and transmission spectra

Figure 4.3 shows the comparison of the transmission and reflection spectra of the FBG as an example. The reflectivity of the reflection spectrum is normalized with respect to the reflectivity of the transmission spectrum.

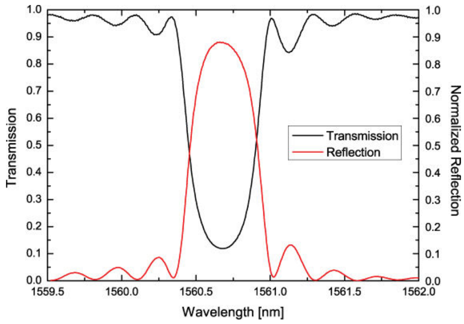

Figure 4.3: Transmission and reflection spectrums of an FBG [4]

4.2.1 History of the FBG

Since the first discovery of the photosensitivity in optical fibers in 1978 [5], it has had a large impact on telecommunications and on sensor systems. Photosensitivity means that the refractive index of a material changes when (high intensity) light is applied to the fiber. The first generation of the FBGs was based on the photosensitivity of silica fiber doped with germanium [6]. In fact, when fiber core irradiated by ultra violet (UV) light, a permanent change occurs in the refractive index of the core. Bragg gratings have been usually written using UV light into photosensitive fibers [1]. Photosensitivity plays a key role in fiber Bragg gratings and several techniques have been developed to improve the effect. Special photosensitization techniques such as doping with Germanium, Boron, Tin, rare-earth elements, or Hydrogen loading and densification, all lead to higher photosensitivity [2-4]. Fiber Bragg gratings in plastic optical fiber on the contrary, have been presented for the first time in 1999 [7]. Polymer fibers have three major advantages when compared to glass optical fibers (GOF). Their higher elasticity, their lower costs and their biocompatibility. The higher ultimate elastic strain (i.e. up to 13% for PMMA [8] compared to 4% for silica) of the polymer fibers enables to increase the sensing range of them. FBGs have been reported in both SI-POF [8] and microstructured POFs (m POF) [9, 10] including SM FBGs and multimode FBGs (MM FBGs). The most PFBGs reported to date had a resonance wavelength around 1550 nm, primarily because of the availability of low cost telecom equipment at that wavelength [8-13]. Total exposure times of 45-100 minutes for step index fibers [11, 12] and 60-270 minutes for mPOF [9] are usually necessary for writing the FBGs (between 2 and 10 mm). Recently, our colleague in institute for Telecommunications (IT) developed a method to write an FBG in microstructured POFs with less than 30 second [13]. Furthermore, in most cases these FBGs have 10 dB of rejection or less in the case of MM PFBGs [9-13]. The preferred technique for the PFBG fabrication is based on the phase mask method due to the intrinsic advantages over the others reported on literature [11-16]. Moreover, PMMA based POFs when compared with silica material, has a larger thermo-optic coefficient and a smaller Young modulus making it much sensitive to external parameters such as temperature , pressure [10] and strain[14,15]. Additionally, PMMA has high water absorption capabilities [16] allowing to detect the environment humidity [8]. These advantages are well attractive especially when large strains can be imposed in POFs without breaking the fiber [18].

4.2.2 FBG inscription

The phase mask technique, which was first demonstrated in 1993 [14], is the most popular and one of the most effective methods for Bragg grating fabrication up to now [11-15]. This technique makes use of phase mask as a key component of the interferometer to generate the interference pattern [20]. The phase mask is placed in contact or near contact with the fiber (POF or GOF), and the UV beam impinges normally to the fiber axis [4]. The beam passes through the mask and is spatially diffracted to create an interference pattern with pitch (Λ) along the fiber axis [16]. Fig 4.4 shows the schematic of the UV side writing setup for inscribing a FBG in Plastic optical fiber. The popularity of the phase mask fabrication method is for many reasons as outlined below [18-26]:

- Simple fabrication process.
- Stable method for producing FBG.
- Minimum sensitivity to mechanical vibrations.
- Possibility of manufacturing several gratings in a single exposure.
- Lower coherence requirement on UV laser beam.
- Easier alignment of fiber

  A disadvantage of the phase mask method stems from the need to have a separate phase mask for each Bragg wavelength. To produce quality gratings, the separation between phase mask and fiber is an important factor.

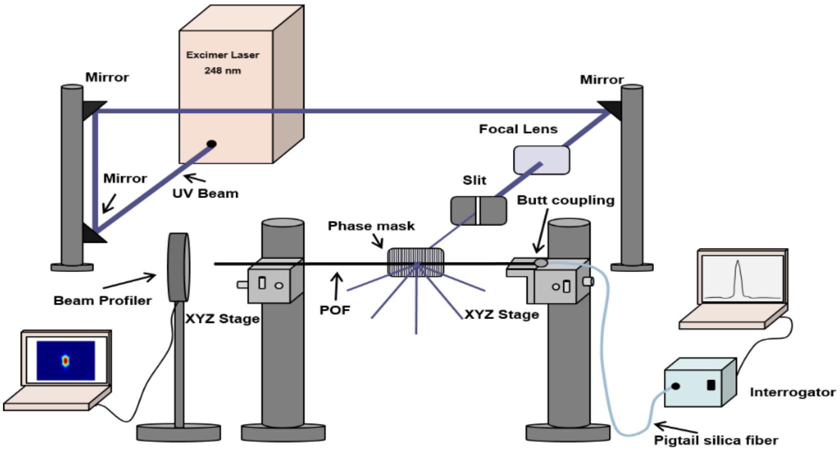

Figure 4.4: Schematic diagram of FBG inscription system [13]

Because of the high attenuation of the POFs in 1550nm wavelength, the length of the POF has to be kept very short. A standard silica fiber is butt-coupled to the polymer fiber. Furthermore, to ensure that the mode is propagated into the core of the POF, light was injected into the silica pigtail fiber and, at the end of the polished POF, a 20 X magnification lens followed by a beam profiler was placed to check if the modes were being propagated in the fiber core.

4.3 Multiplex technologies over POF

The standard communication over plastic optical fiber uses only one single channel [26]. As discussed in previous chapter, the maximum link length and capacity of the POF system in point to point link configuration is limited due to the modal dispersion. One possibility to open up this bottleneck is taking the advantages of the parallel transmission over one single fiber. This technology is called wavelength division multiplexing (WDM) and it was an extremely successful technology for single mode glass optical fibers over the last two decades. In the WDM systems, light wave at several different wavelengths can be transmitted by a single optical fiber without interfering with each other's. In glass optical fiber technology, the use of the WDM in the infrared range at about 1550nm is well established [27-28]. The two key components of a WDM system, beside the optical fiber, are multiplexer and a demultiplexer devices.

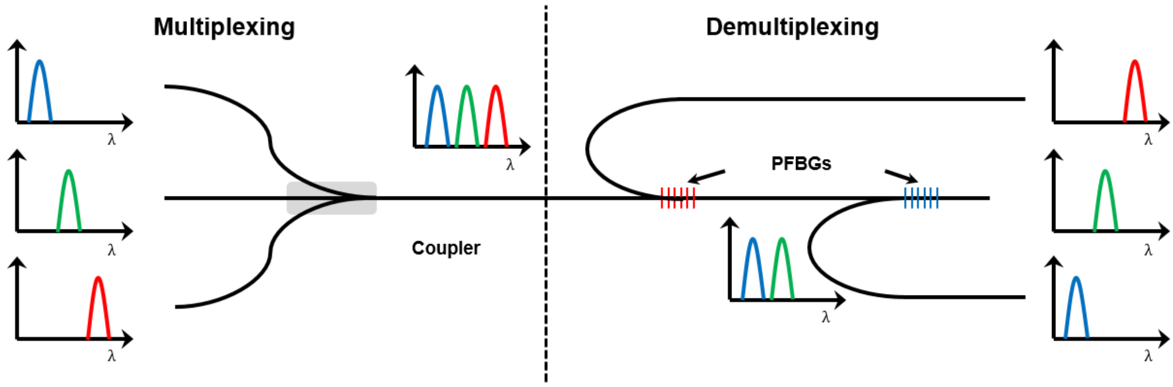

Figure 4.5: Simple WDM system

The Multiplexer integrates every wavelength to a single waveguide and is placed before the single fiber (See Fig. 4.5). Each of these wavelengths will be in the grid according to the POF transmission windows. On the other hand, the second element, the demultiplexer, is placed behind the fiber to recover every separate wavelength. These two components are well known for infrared telecom systems especially in C+L telecommunication band [27]. But for POF development they must be developed completely new, because of the different transmission windows**.** One typical element in WDM systems is a fiber Bragg Grating. In principle, a Bragg grating selects a specific wavelength (one for every mode) out of a broad spectrum and reflects it. By optimizing all parameters like the refractive index change, the length of the grating, etc. any desired filter, both narrowband and broadband, can be constructed [29]. Since there is no energy exchange between different wavelengths in a communication system, each wavelength can be used as a separate channel to carry information. Therefore, the bandwidth of a fiber is multiplied by the total number of channels used. Therefore, using FBG is a simple but powerful technique to increase the bandwidth of a telecommunication system. An example of the use of the FBG in the WDM system is shown in Fig.4.5, where three different wavelengths in different colors are combined in transmission side and FBGs are used in the receiver side to construct the optical signal. Fiber Bragg gratings are playing an important role in the receiver side, where each FBG is used to have access to a specific wavelength. The WDM techniques are very well established for glass optical fiber. To use its capabilities in plastic optical fiber application, the commercially available components for this purpose are listed in next section.

4.3.1 Commercially available optical components

In order to better analyze the feasibility of the WDM scheme over plastic optical fiber in real scenarios, we highlight the commercially available components for plastic optical fiber. The important issues must be taken to account are:

- **Cheap and easy to use:** Thinking in a house environment, the chosen component should be cheap. It must be accessible to the user. We shouldn't choose a great performance fiber but too expensive. The optical components should be easy to install and maintenance without requiring especial tool and expertise.
- **Flat and low attenuation levels**: The working wavelength for WDM system should have a flat and low attenuation profile in the fiber.
- **Transmission windows**: It's important that in the transmission window there were components working on supported transmission windows (couplers, transceivers, receivers).

4.3.1.1 Optical fiber

Taking to account the issues discussed above, the type of the plastic optical fiber that suites best in our requirement is Perfluorinated polymer based graded index POFs. This kind of POFs with its low attenuation between 850 and 1310nm wavelength which allows the use of emitters and receivers used in glass fibers. It also has low intermodal dispersion levels in comparison to the SI-POFs. Moreover, it offers the higher product Bandwidth in comparison to other types of the POFs. The attenuation profile of the chosen PF-GI-POF is shown in Fig.4.6.

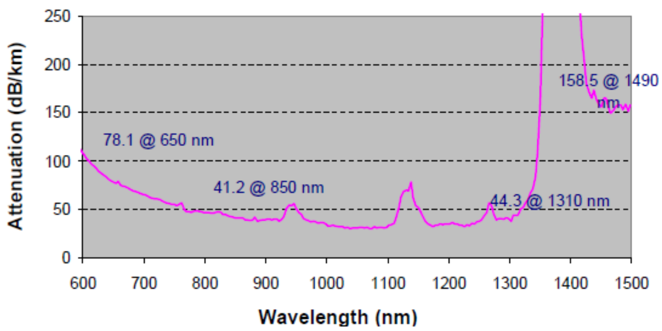

Figure 4.6: Attenuation profile of the PF-GI-POF

4.3.1.2 Optical Transceivers

The main advantage of using PF-GI-POF beside their low attenuation and lower modal dispersion is that we can user the same type of sources that we use in glass optical fibers, because both use the same spectral range between 850 nm and 1300 nm. Table 4.1 shows the best commercial optical transceivers that fits well with the chosen fiber with core diameter of 50 µm.

Product	wavelength	Power (mw)	Full width at half maximum (FWHM)	Data sheet	Price (€)
VSEL-850 (Finisar)	850nm	1.85	0.85 nm	Link	49.95
VSEL-980	980nm	1.85	0.8nm	Link	54
ML925B45F	1310 nm	10	1nm	Link	67
DFB lasrr	1064 nm	20	14nm	Link	130

Table 4.1: Commercial light sources for POF fibers, including their specifications

4.3.1.3 Couplers

Couplers have an important role in a multichannel transmission because this device will couple different signals on the same optical fiber. There have been many techniques of fabricating POF couplers. These techniques include twisting and fusion, side polishing, chemical etching, cutting and gluing, thermal deformation, molding, biconical body and reflective body [25]. The main drawback of the use of POF couplers as multiplexers are: a) their high associated insertion losses, typically up to 8dB per branch [26] if we consider 3:1 and 4:1 POF couplers. Some of the commercially available couple for plastic optical fiber is given in table 4.2.

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	48
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**	57
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	58
IF 544 (4X4)	25:25:25:25	n.a	n.a.	Link	54

Table 4.2: Commercial couplers

4.3.2 Reported WDM system over POFs

A big number of different technologies had been developed for WDM multiplexers for single mode glass fiber systems. Arrayed waveguide gratings (AWG), fiber bragg gratings (FBG) are some of the most successful versions. In comparison to the SMF, POF has some limitation for using these technologies:

- POFs are multimode fibers. That makes the use of AWG, Single mode FBG and Mach-Zehnder not possible.
- POFs has large core diameter and NA which results in much bigger optical components.
- Fiber amplifiers for the compensation of multiplexer loss for Multimode components are not available.

The first multi transmission over plastic optical fiber was presented in [33]. In this work, the combination of analog control (10 kHz) and video (6 MHz) data over 50m of the GI-POF is presented. Two LEDs at 660nm and 830nm is used as a transmission. In [34, 35] 2×2.5m Gbps data over a 750 µm PMMA-GI-POF is reported. Two laser diode in 645nm and 675 nm were directly modulated in 2.5 Gbit/s each. The transmission distance was 84 m. 10.7 Gbps [37] and 14.7 Gbps [38] data transmissions employing the offline-processed discrete multitone (DMT) modulation over 50 m SI-POF was reported using four channels. Four laser diodes operating at 405, 450, 515, and 639 nm were used as a transmission. The 4×1 coupler is used as a multiplexer. The demultiplexer solution in these cases was based on bulk optical components see Fig 4.7. The main problem in this demultiplexing technique is high optical loss for each optical channel, typically is 4 dB (optimistic) and the optical crosstalk is 1 dB. This technique also requires many elements (typically the number of elements doubles the number of channels). In next section, the solution based on the FBG written in POF as a filter in WDM system is presented.

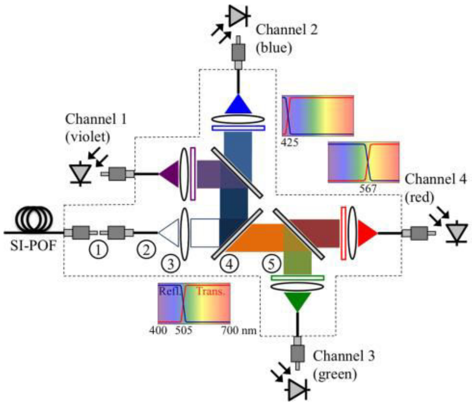

Figure 4.7: Demultiplexer setup in [37], [38]

4.4 Proposed WDM over POF

A new method to increase the capacity of the plastic optical fiber based on the fiber Bragg grating is demonstrated. We use the wavelengths division multiplex (WDM) scheme to transport the data over the plastic optical fiber. Based on these techniques, the relatively economic devices are chosen for that purpose. For demonstration purposes, we numerically investigated a WDM over POF point to point link with capacity of 40 Gbit/s (4x10 Gbit/s) and 100 Gbit/s (10x10 Gbit/s). The transmitter is based on several optical sources from table 4.1. The optical sources are directed modulated with a 10Gb/s NRZ data. The wavelengths are selected from the visible and infrared region, where the PF-GI-POF has its minimum attenuation. The 10G NRZ signals from the bit generations are ideally multiplexed and transmitted on a PF-GI-POF which has an attenuation lower than 40 dB/km. The receiver side the PFBG operating in the same frequency as the VCSELs are used for dropping the 10 Gb/s data's. A 3 dB optical coupler is used to access the reflected signal from the Plastic FBG. The optical receiver has a dark current of 10nA and thermal noise of 0.18×10^{-24} W/Hz. The maximum transmission distance determined for a BER=10^{-9}. The schematic of the simulation scenario is presented in Fig.4.8.

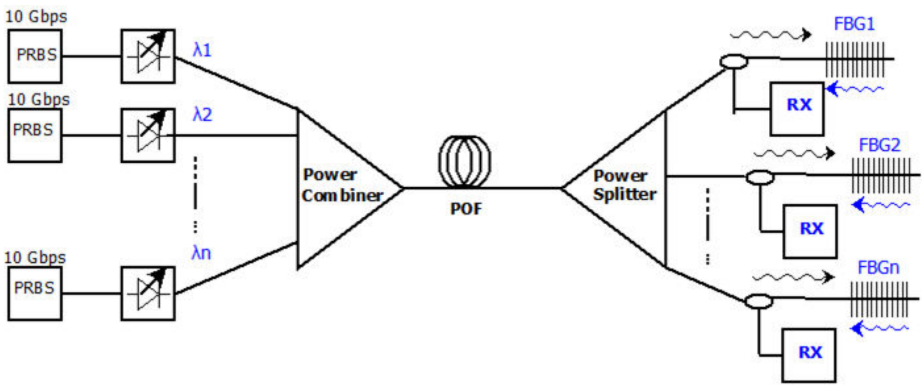

Figure 4.8: Schematic of WDM over POF with **n** channels

4.4.1 Simulation results and discussion

Simulation results are carried out using commercially available optisystemV.11 from Optiwave Company. The BER measurement and eye diagram as a function of received optical powers for different length of the PF-GI-POFs are optimized to reach to the threshold of BER=10 $^{-9}$ which corresponds to the Q = 6. Figure 4. 9. Compares the obtained results to those reported in the literature [40, 41] for identical capacities.

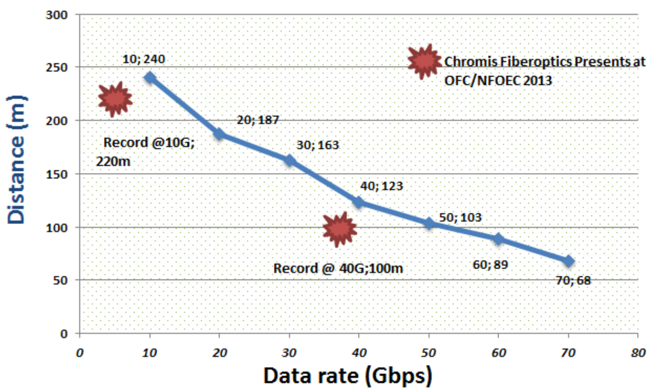

Figure 4.9: Maximum distances obtained for the different configurations and comparison with the best results reported at the literature.

Table 4.3 summarizes the maximum transmission distance obtained by the tested fiber for a total capacity of 40Gbit/s (4 channels) and 100 Gbit/s (10 channels). The optimum results also compared with the results in the literature. Higher transmission distances could be obtained if one considers forward error correction (FEC) to increase the BER threshold. The results show that using PFBG technology for WDM POF transmission can be an interesting approach to increase the capacity of POF transmission, in a relative low cost and complexity and without dropping the maximum transmission distance.

Capacity	Length	BER	Q
40Gbps [40]	100m	$<10^{-12}$	-
112Gbps [41]	100m	7.4×10^{-4}	-
40G WDM POF	123	4.46×10^{-9}	5.745
100G WDM POF	68	1.81×10^{-9}	5.9

Table 4.3: Output of BER analyzer in different length of the PF-GI-POFs.

4.4.2 Specifications

In a typical 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 4.4. Here we have included the previously selected components in four WDM channel with their current prices (July 23, 2016).

Components	**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	160 m	136
GigaPOF Connectors	4	6	24
Receiver device			
FGA01InGaAsPhotodiode	55	2	110
FDS025 Si Photodiode, 47 ps Rise Time	30	2	60
Demux	Approx. 50 € (Lab.)	1	50
Installation work	20 €/h	50	1000
Total			582/1582

Table 4.4: House link WDM POF budget

In both source and receiver device we haven't included the electronic layer. 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 mentioned in the table would be cheaper too.

4.5 Summary

In this chapter the effect of a Bragg grating on the light propagation in a fiber is explained. Only the wavelength that satisfies the Bragg equation will be reflected while the other ones will pass. In order to produce a Bragg grating in an optical fiber, it has to be photosensitive, a property that can be increased by several doping techniques. Bragg gratings is a key element in several passive components such as filters, couplers, dispersion compensators, amplifiers

and sensors. The production and characterization of FBG in plastic optical fiber is described as well as the potential applications in optical communications and sensors. As a sensor, Plastic FBG have higher temperature sensitivity, although lower maximum achievable temperature. It also has higher strain range due the intrinsic properties of the plastic. PFBG technology can also be used to allow WDM over POF and, therefore, increase the capacity of POF communications without lowering the maximum transmission distance and keeping the costs relatively low. The visibility of the WDM schemes over plastic optical fiber based on the commercially available passive optical components is analyzed. The main result is that the reported total capacity of these systems is higher than the single channel. However, it is still an expensive solution to be used at the home networks. 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.

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5 Radio over Plastic Optical fibers for Home Network Applications

5.1 Introduction

The radio over fiber system is the most used solution to integrate the capacity of optical fiber with the flexibility and mobility of wireless networks to support data traffic volumes on demand by the end users. As discussed in previous chapters, PF-GI-POFs seem a very attractive alternative in home access networks in compare to the "classic" single/multimode glass optical fibers and CAT technology because of their easy installation and low prices. In this chapter, we experimentally propose and investigate the performance of the low cost digital radio over fiber (DRoF) system over multimode GI-POF in home network scenario with coexistence of the single mode fiber (SMF) in optical access network. An experimental evaluation of DRoF links for various optical fiber attenuator is also conducted, considering the transmission of RF signals conveying QAM symbols. The experiment results show that with the coexistence of 20km of single mode fiber (SMF) and 50 m of the GI-POF, 1.25 Gb/s baseband signal with 16 quadrature amplitude modulation (QAM) can be accommodated in our proposed DRoF scheme.

5.2 An overview of the wireless system

Through the world, with the rapid growth of personal mobile electronic devices, people use increasingly their devices in a wireless way, in particular thanks to the popular Wi-Fi (Wireless Fidelity), the commercial name of the products based on the IEEE 802.11 standards [1]. Wireless communications have been able to provide flexible, low-cost and comfortable services according to the consumer's need. As a result, Wi-Fi is today widely available and is integrated everywhere: in computers, gaming consoles, smartphones, tablets, printers, etc.... Large number of technologies and systems have been developed to meet different requirements of users in terms of their coverage and supported data rates as shown in Figure.5.1.

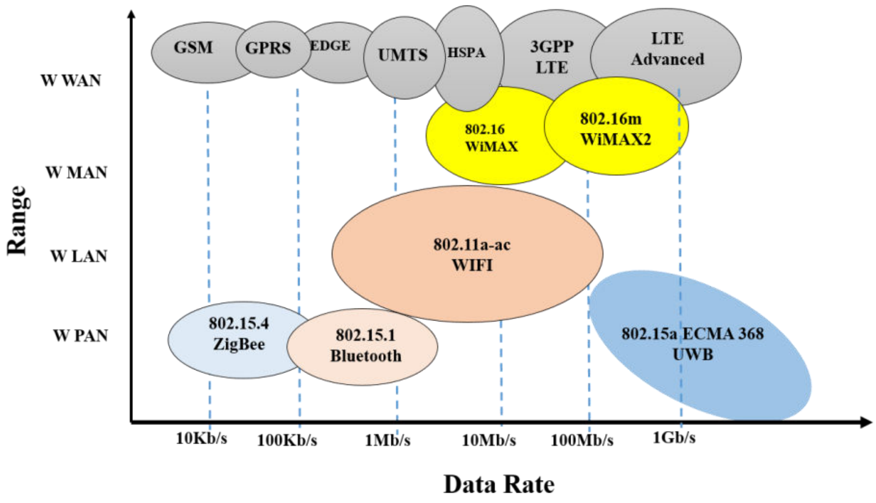

Figure 5.1: Current and emerging wireless communication technologies [1-4].

The wireless broadband or wireless access technology that are classified into worldwide inter-operability for microwave access (WiMAX), WiFi, mobile broadband, satellite based technologies and wireless network. The recent wireless broadband technology is for mobile and fixed that is WiMAX. The standard of IEEE 802.16e for Mobile WiMAX and IEEE 802.16d for fixed WiMAX [2, 3]. Based on this two standards, the (WiMAX) has been able to provide up to 1 Gbit/s [3].

With the evolution of wireless communication techniques, the mobile technologies from second generation standard (2G) have moved to 3G/3.5G even 4G standards [4]. The 3rd Generation Partnership Project (3GPP) Long-Term Evolution (LTE) technique (incl. LTE- advanced) has been widely agreed for the next generation of wireless communication for mobile phones and terminals [4, 5]. The next generation of mobile networks needs to meet the exceptional bandwidth demand expected for the coming years. Recent studies predict that in 2020 networks should be prepared to support an increase of up to 1000 times of total traffic compared to what is currently available [6]. Services such as ultra-high definition video streaming, online gaming, machine-to-machine communications and cloud computing are examples of bandwidth hungry applications that are fast becoming an essential part of consumer’s lives. This traffic consumption is mainly due to the growing number of wireless devices that are accessing mobile networks, it was estimated that the number of connected mobile devices exceeded the world’s population [7]. In average, is reported that the global end user traffic will grow up 21% from 2013 to 2018, while for the same period of time mobile traffic has a growth perspective of 61% [8].

To handle this continuous need from increasing in traffic demands, the telecommunication operators have been exploring and deploy new technologies and network configurations to improve their end user's experience. The conventional microwave links connecting the BS with the core of the network cannot provide enough bandwidth to support those transmission rates and scenarios, which represents a big challenge from the operator's view [7-10]. Connecting the antenna with the backbone over optical fibers can solve this gap.

5.3 Radio-over optical fiber

Radio-over-Fiber (RoF), as its name suggests, is a technology that uses the optical fiber to transmit radio frequency (RF) signals. The loss of an RF signal in free space transmission line increases with frequency because of the reflection and absorption in this medium [10]. So, the transmission of the RF signal in free space over a long distance is problematic and costly due to the necessity of regenerating equipment's [10-12].

The idea of the RoF is to transmit the RF signals over an optical fiber as long as possible to get advantage from the very low attenuation of optical fiber, and then to spread out the RF signal over small distances, offering a high bit rate (>Gbps) [13,14]. In a ROF system, light is modulated by the radio signal and is transmitted over an optical fiber link from a central office to a number of remote locations where the wireless access points are placed. A ROF system consist of a laser / photodiode pair at the central site, a laser / photodiode pair at the remote site and one or more optical fibers linking the two sites. Figure5.2 shows the component parts of this basic ROF system. On the transmission side at the central station, the RF signal is directly modulated by laser diode and the resulting signal is transmitted to the remote antenna unit (RAU) over the optical fiber. At the RAU, the transmitted RF signal is detected by the photodetector and recovered by direct detection to be amplified and radiated by the antenna, and transmitted to the mobile unit (MU).

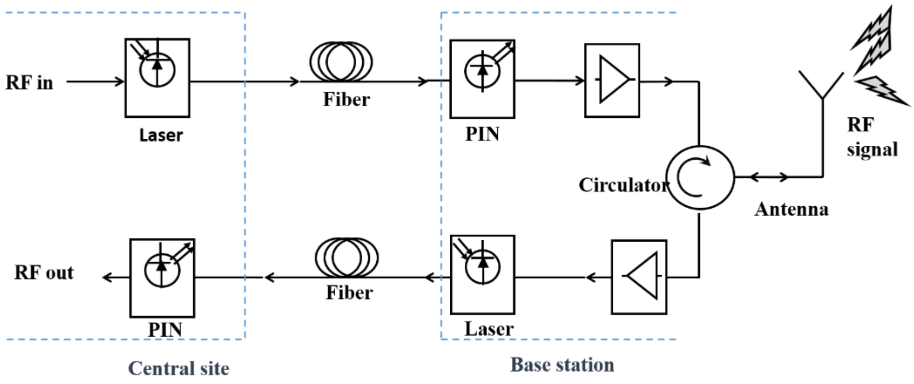

Figure 5.2: General schematic of the ROF system

There are several main advantages of using ROF systems compared to conventional RF wireless technologies which can be highlighted as following [10-14]:

High bit rate: Optical fiber suffer very low attenuation compared to other transmission environments. The high bandwidth is also a positive point in radio systems over fiber. There are three transmission windows offering low attenuation, particularly 850 nm, 1310 nm and 1550 nm.

• **Low cost:** The low complexity and the wide deployment optoelectronic devices (laser diode, photodiode) in telecommunications keep the optical components as a low cost as compared to other communications systems.

• **Electromagnetic Interference (EMI)**: The EMI is any electromagnetic disruption due to the radiation of any devices around the transmission link or the devices of the transmission link. The operation frequency of the optical communications is few hundreds of THz is very far from the operation wavelength of radio frequency communications and electrical devices. This characteristic makes the optical link a dielectric guide without any EMI.

• **Health immunity:** Optical communications are considered to be a healthy system with the absence of all types of radiation that can be harmful for health.

• **Free license fees:** Unlike radio and microwave links, optical transmission is not licensed and the suitable wavelength for a system can be freely chosen, without any fees.

• **Security of transmitted data:** The optical signal cannot cross wall and opaque surfaces, which makes impossible to any person outside the room where the wireless optical transmission is done to detect the signal and to access the data.

5.3.1 Analog ROF

The analog ROF systems contains transmitter, transmission medium and receiver, as shown in Figure 5.3. In the transmission side, an electric carrier is modulated to an optical carrier and is then transmitted in the fiber. At the receiver, after detection, the signal is converted back to the electric field and finally propagated by the antenna to the receivers.

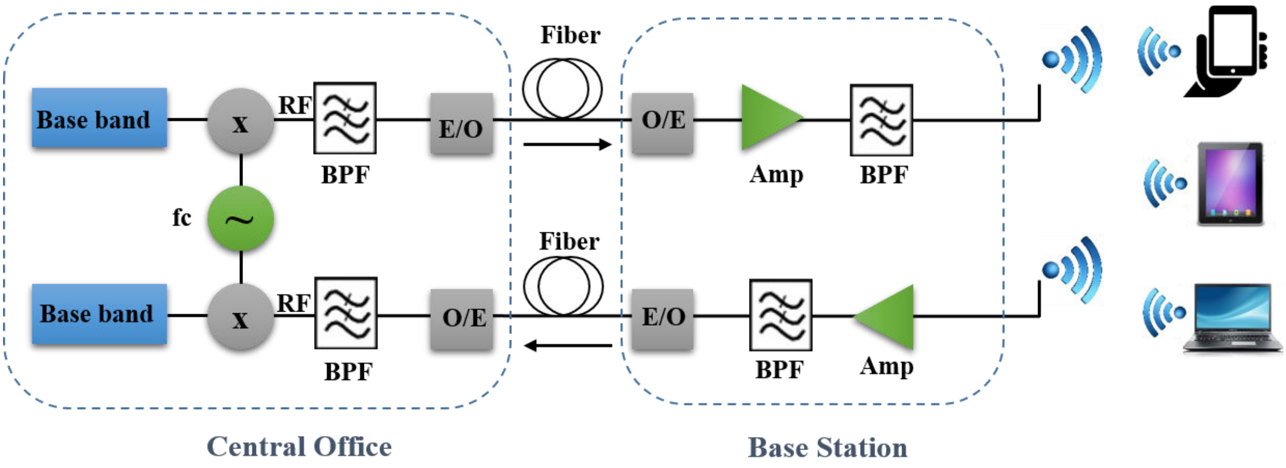

Figure 5.3: basic architecture of an analog RoF system

The most important block of CO is electrical-to-optical (E-O) conversion wherein Optical Modulators are used [15]. For low frequency signal transmission, internal modulator or directly modulated laser is sufficient but higher frequency applications external modulators like Mach-Zender are preferred. For better performance of ROF, E-O and O-E Convertors should have low loss and should be highly linear [14-16]. The main advantage of the transmitting the analog signals over optical fiber is because of the simplicity of the antenna, where depending on the transmitted frequency it may contain only amplifiers and electronic receptors. However, it comes at the expense of the large number of the noises introduced by filters, amplifiers and photodetectors [15-16].

5.3.2 Digitised ROF

The digital signal processing has revolutionized modern communications systems. Digital systems are flexible and more conveniently interface with other systems [17], and are more reliable and robust against additive noises of devices and channel, and achieve better dynamic range than the analog systems [17]. In a digital ROF (DRoF) system, an electrical RF signal is digitized by using an electrical analog to digital convertor (EADC) with frequency sampling defined by the Nyqiust or bandpass sampling theorem [18]. Then, the generated digital data modulated by optical carrier wave either using direct modulation technique or by using an external electro-optical modulator and transmitted through the optical fiber. In the receiver side after detection, the signal is converted to the electrical domain and then converted back to analog via a digital to analog convertor (DAC). In the final stage, the signal is propagated by the antenna to the receivers. The transmission to the central office (CO) in the reverse direction to the antenna CO, follows the same principle of operation described.

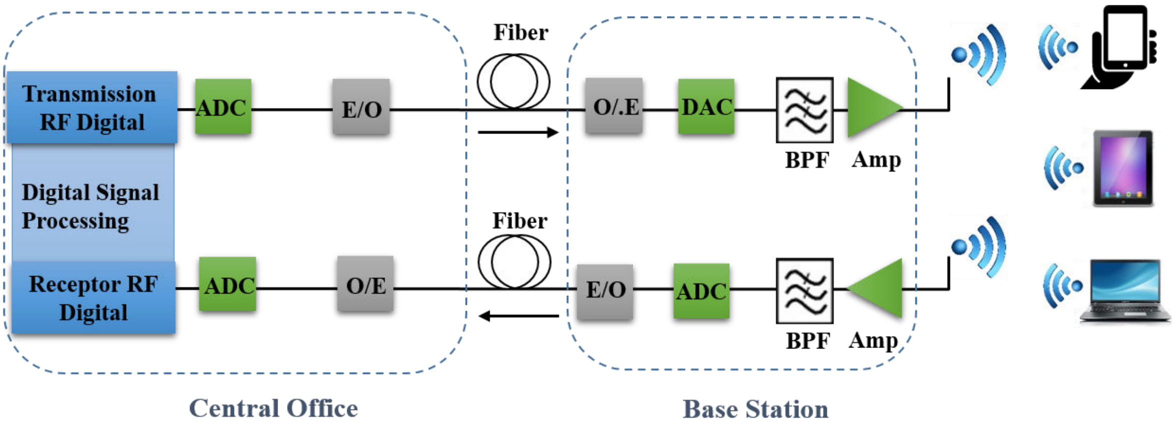

Figure 5.4: Basic architecture of a DRoF system

The Advantages of Digital optical links in comparison to the analog ROF are [17-19]

- Large bandwidth optical link can be achieved
- Dynamic range is independent of the fiber distance
- Digitized RF-over-fiber can be based on low-cost digital transmitters and receivers
- It has high dynamic range which can be sustained over a long distances in comparison to that of analog optical links

Although, DRoF schemes are an interesting alternative to their analogue ones, but during analogue-to-digital conversion in the ADC, the system is affected by different sources of noise such as jitter and quantization [20]. The ADC bit resolution is one of the most important parameters in DRoF system which is related with main source of noise (quantization noise), and also the system's performance due to contribution to overall optical line rate [19-21].

5.4 Digitised Radio over Plastic Optical Fiber for In-Home Network

In this section, we propose a low cost DRoF system to deliver digital baseband from wireline and wireless users in home access network to the 5G mobile front haul. GI-POF considered as a reliable, low networks capital and operational expenditure, and broadband backbone network to connect the next generation home multi-cells/layers networks to the mobile front-haul. We present experimental results that address the impact of the ADC bit resolution on the performance of the DRoF system, as well as the impact of the GI-POF on the both analog and digital ROF systems. The experiment results show that with the coexistence of 20km of single mode fiber (SMF) and 50 m of the GI-POF, 1.25 Gb/s baseband signal with 16 quadrature amplitude modulation (QAM) can be accommodated in our proposed DRoF scheme

5.4.1 Digitised radio over GI-POFs system

DRoF transport schemes that combine both optical and electronic digitisation are being studied and pointed as viable alternative solutions to ARoF systems [9]. The conceptual diagram of the proposed scenario to evaluate the implementation of the DRoF system in home access network is illustrated in Fig.5.5. The in-building network is supported by 50m of the GI-POF with attenuation of the 50dB/km@1550nm. The digitised signal at the output of the central office, after passing 20 km of the standard SMF (SSMF) and through the building with multimode GI-POF, is propagated by the antennas to the end users. This implementation scheme can be implemented not only for more recent technologies (e.g., 4G and 5G), but also for legacy technologies existing in the network infrastructures such as 2.5G, 3G, WiFi and other.

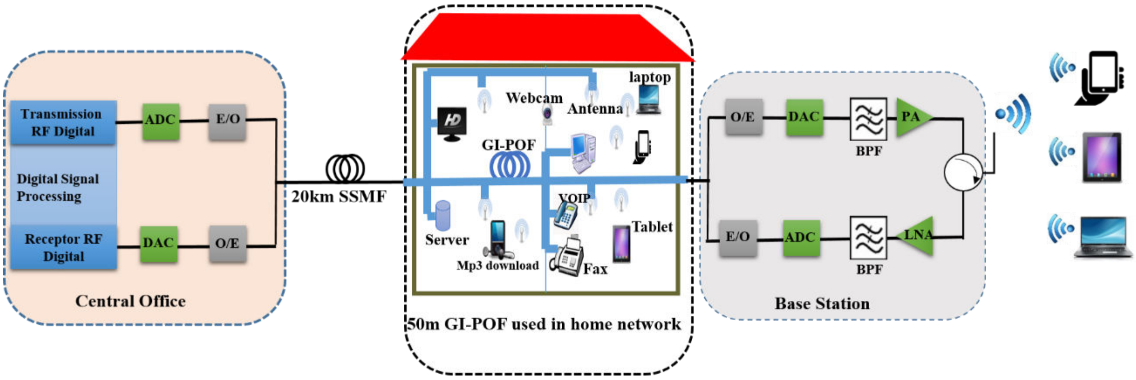

Fig. 5.5: Diagram of the proposed digitized radio-over-fibre architecture. E/O: Electrical to Optical conversion, O/E: Optical to Electrical conversion, ADC: Analogue to Digital Conversion, DAC: Digital to Analogue Conversion, BPF: Band-Pass Filter, PA: Power Amplification, LNA: Low noise Amplifire.

Carrier Frequency	5×10^9	Hz
Mid Frequency	400×10^6	Hz
Modulation Format	16 QAM	--
Attenuation SMF	~0.2	dB/km
Attenuation GI-POF	50	dB/km
Dispersion SMF	17	dB/(nm*km)
Dispersion slop GI-POF	<0.6	ps/(nm^2*km)
Laser Linewidth	100×10^3	Hz
MZM extension ratio	25	dB

Table 5.1 Parameters of experimental components DRoF assembly.

5.4.2 Experimental setup

The schematic of the experimental setup used to evaluate the radio over fiber systems in home network applications is illustrated in Fig. 5.5. From the CO to home, the analogue RoF system is constituted by an Arbitrary Waveform Generator (AWG; M8190A, Agilent), which is responsible for generation of the 16-QAM RF signal with a 5 GHz carrier frequency, downconverted to intermediate frequency (IF) of 200 MHz by means of a local oscillator (LO) at 4.8 GHz. The signal is externally modulated by a MZM in an optical carrier sourced by an External Cavity Laser (ECL). The output optical signal is connected to the 20 Km of the standard SMF until to reach inside the building. In order to avoid the misalignment between two fiber cores, two collimators (Col-A, Col-B) are used. At the receiver side, one avalanche photo diode (APD) converts the optical signal to electrical domain which is up-converted to original frequency (5 GHz) using a LO at 4.8 GHz. In the last step, the electrical output signal is read by the digital oscilloscope (Tektronix DPO 720004B), which removes a portion of the signal in time, and this sample is then analyzed in offline and performance evaluation is performed.

In contrast to the analogue RoF, DRoF signal is digitized by ADC before optical transport. Here, the IF (200 MHz) is sampled at 1.25 GHz and quantized. The stream of bits is then uploaded into the pattern generator (serial BERT Agilent N4906B). At receiver side and after detection, the DAC converts the serial digital signal to parallel. After this process the signal is reconstructed similarly as in the analogue RoF technique. For both systems, the QAM mod/demod, LO and ADC/DAC operations are implemented off line in VPI@ and MATLAB.

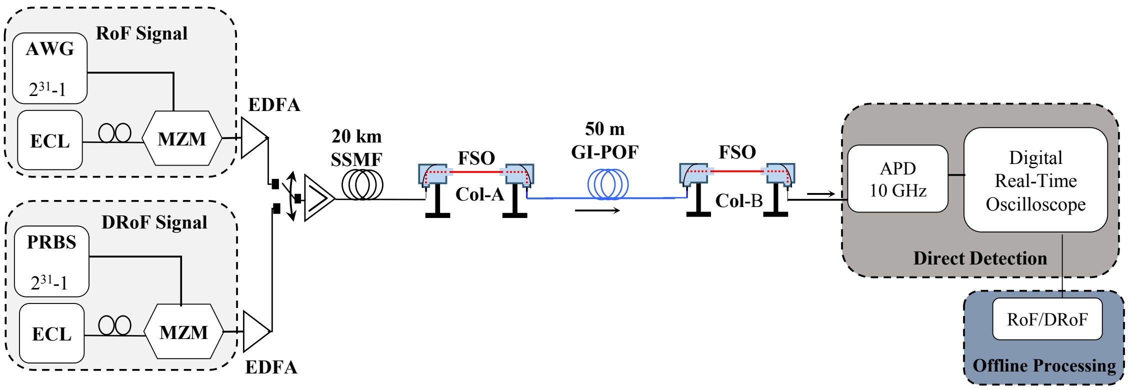

Fig. 5.6 Experimental scenario with proposed DRoF system. AWG: Arrayed waveguide gratings, ECL: External Cavity Laser, PBRS: Pseudo Random Binary Signal, APD: Advanced Photodiode, MZM: Mach-Zehnder Modulator, FSO: Free Space Optic, EDFA: Erbium-Doped Fiber Amplifier.

5.4.3 Experimental results and discussion

In this section the results are discussed. To a fair analysis, both systems (ARoF and DRoF) were tested under same settings with MZM at PI/2, optical input power of 3 dBm. The signal IF-200 MHz with 1.25 Gbit/s modulated in 16-QAM it was also considered for analog and digital transmissions. However, in DRoF system were made tests with signal digitised with 4 and 8 bits resolution. As in the digital system the overall data rate is given by the product of the bit resolution and sampling rate used at ADC (e.g., 1.25 GHz), the bit rate transmitted at the fiber is, respectively, 5 Gbit/s and 10 Gbit/s for 4 and 8 bits, which corresponds the line rates 5 and 8 of CPRI specification [24]. As the attenuation is

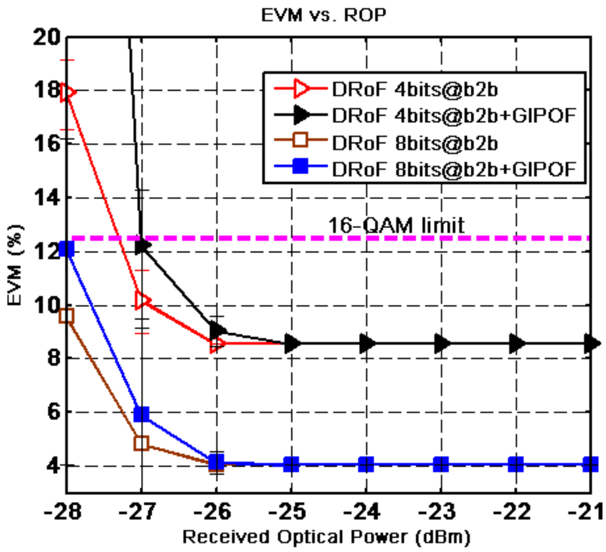

Figure 5.7: EVM versus Received Optical power for DRoF in an isolated scenario with b2b and b2b+GIPOF

a critical parameter in the radio over fiber transmissions, the performance of system was measured with Error Vector Magnitude (EVM) as function of received sensitivity. The variable optical attenuator (VOA) was placed at the link before signal at receiver side to adjust the optical power received, in all the scenarios considered: b2b, b2b+GI-POF, 20km@SSMF and 20km@SSMF+50m GI-POF. The performance of the proposed DRoF system in home network is analyzed with co-existence of the 20 Km of the standard SMF in access network. The impact of the different ADC bit resolutions on the DRoF system as a function of the EVM, when employing 16 QAM scheme, for b2b, b2b+GI-POF (50m) is plotted in Fig. 5.8. As it can be seen from this figure, for tests with and without GIPOF the EVM remains constant up to certain received power, -25dBm for 4-bits and -26 dBm for 8-bits, and then decrease due to errors at the received side, mainly, introduced by thermal noise at APD. After those, the performance with GI-POF transmissions starts to degrade more than b2b scenario. In -27dBm received power, both transmissions are inside the 16 QAM limit [22].

However, in the coexistence scenario (Fig.5.8) in which is considered 20km SSMF with 50m GI-POF, the penalties are more significant wherein after -25 dBm the performance of GI-POF transmission degrades severely due to modal dispersion, which induce restrictions in the received signal. It is also important to notice that the increased number of the resolutions means complexity and power consumption, therefore potentially increased cost in digital systems. So, in order to achieve an acceptable performance (EVM below the 12.5%), only 4-bit resolution ADC is enough.

For ARoF system the analysis is similar to DRoF systems. As it shown in Fig.5.9, in comparision to the DRoF, the performance of ARoF transmission decreases with increasing attenuation. In coexistence scenario, the EVM for analogue transmission becomes greater than the threshold level at the received power level of -25dBm. Nevertheless, since the transmission media are the combination of SMF and GI-POF, the penalties from modal dispersion is more than DRoF system. The EVM clearly shows that

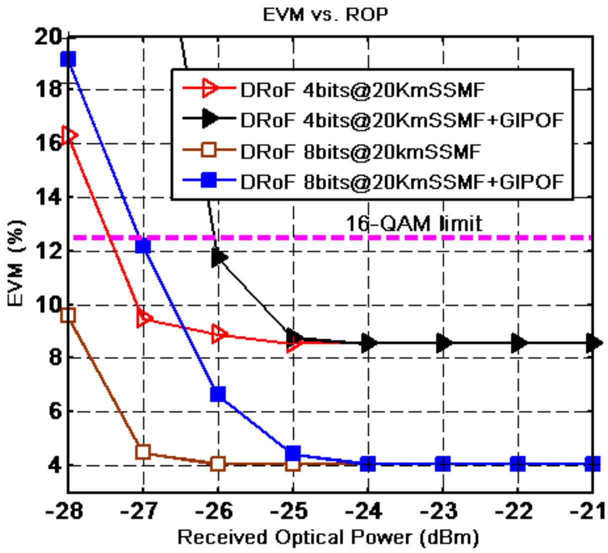

Figure 5.8: EVM versus Received Optical power for DRoF in coexistence scenario with SSMF and SSMF+GIPOF.

performance of DRoF systems remain constant up to a certain level received power (-25 dBm), and only in -26 dBm and -27dBm the system suffers a small penalty in coexistence scenario. This ensures that digital transmission can operate for long distances having a better sensitivity than analogue RoF system.

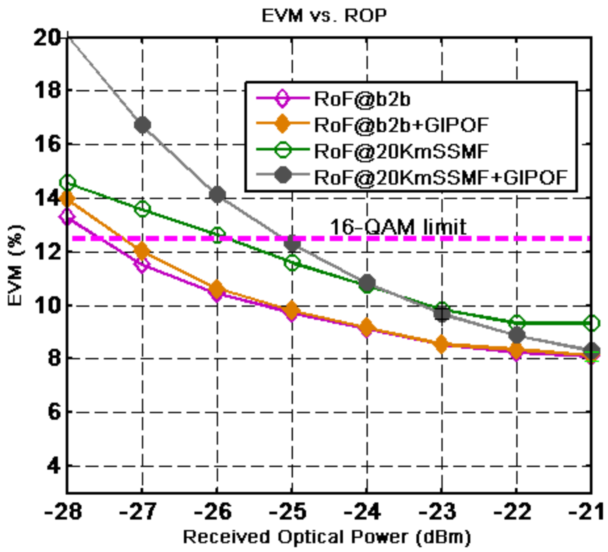

Figure 5.9: EVM for different scenarios in Analogue ROF.

5.5 Summary

In this work the transmission of RF signals in conventional DRoF systems to deliver digital baseband for wireline and wireless users in home access has been presented and evaluated. The viability of the DRoF system to support the standard base band transmission in home access networks is also investigated. Results show that the system has a constant behavior in terms of EVM until a certain optical power received, and the greater the number of bits of resolution. The experiment results show that with the coexistence of 20km of single mode fiber (SMF) and 50 m of the GI-POF, 1.25 Gb/s baseband signal with 16 quadrature amplitude modulation (QAM) can be accommodated in our proposed scheme.

Furthermore, the proposed architecture is economically competitive for either upgrading installed systems as well as for new deployments.

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6 Chapter6 Photonic crystal fiber in telecommunication applications

6.1 Introduction

Photonic crystal fibers (PCFs) are a class of optical fibers that uses photonic crystal cladding and were developed in early 1990s. The continuous and innovative theoretical and experimental works on the photonic crystal fibers shows that they possess fundamentally exceptional properties and over comes many limitations of conventional optical fiber, i.e. being endlessly single mode, high nonlinear coefficients, dispersion engineering and guiding light through hollow core. Considering these unique as well as exceptional properties of the PCFs, this chapter mainly focus on their applications in the telecommunication area. The work described in this thesis is motivated by the need to explore new PCFs designs and to correlate them to the physical and optical properties that can be achieved. The optical properties and their application in telecommunication field is discussed in section6.2. In section 6.3, analytical and accurate numerical tools will be employed to optimize the index guiding PCF structures. The index guiding PCFs made of different highly nonlinear materials with two novel structures will be optimized in order to achieve ultra-flat dispersion, high nonlinearity and low confinement loss over a broad range of wavelengths in telecommunication band.

6.2 Relevant optical properties and applications

Due to the huge variety of air-holes arrangements in PCFs, they can offer a wide possibility to control the refractive index contrast between the core and microstructured cladding. Novel and unique optical properties can provide by them which is impossible by the standard single mode fibers. Controlling their optical characteristic is a critical issue for some specific applications. Here I briefly explain the different physical effects that happen during light propagation down a PCFs.

6.2.1 Fiber losses

The first effect we consider is the fiber loss or attenuation. The attenuation constant, α, is an energy loss during the transmission in the fiber. It is calculated using the following equation [1]:

$$\alpha\left[\frac{dB}{m}\right] = -\frac{10}{L}\log(\frac{P_t}{P_o}) \qquad (6.1)$$

Where, P_0 is the power launched at the input of a fiber, Pt is the transmitted power, L [m] is the fiber length. Two main factor that causes the loss in the standard fiber are material absorption and Rayleigh scattering. In PCFs, the major attenuation mechanisms are: absorption, scattering, bend loss and confinement loss [2-4]. Because the pure silica which is commonly used as a host material in the core of the index guided PCFs has a lower Rayleigh scattering loss than standard germanium-doped fibers (used in the core of SMFs), thus pure silica holly fibers have lower loss than standard fibers. Losses in hollow-core fibers are limited by the same mechanisms as in conventional fibers and in index-guiding PCFs. However, there is the possibility to reduce the nonlinearity of them below the levels found in conventional optical fibers since the majority of the light travels in the air core, in which the scattering and absorption in air are nearly 1000 times lower than in glass. Moreover, due to the finite number of air holes which can be made in both solid core and hollow core PCFs cross sections it is necessary to consider another contribution to the losses, that is the leakage or confinement losses [5]. The confinement loss can be calculated from the imaginary part of the complex effective index (n_{eff}) by [5]:

$$LC\left(dB/m\right) = 8.686 k_0 \operatorname{Im}\left[n_{eff}\right] \quad (6.2)$$

Where, $K_0 = \frac{2\pi}{\lambda}$ is the free space wave number. The confinement loss is determined by the geometry of the structure and it has been shown that increasing the number of rings of air holes in the PCFs can reduce the fiber loss by improving the confinement of the mode [6].

6.2.2 Dispersion

Dispersion is another key optical property of the photonic crystal fiber, which is characterized by the wavelength dependence of the group velocity of the guided mode. The total dispersion of the PCFs can be calculated, as the sum of the material dispersion which is defined by the Sellmeier equation of the materials [7] and the waveguide dispersion (can be controlled by the design parameters). The effects of fiber dispersion are expressed by applying Taylor expansion for the propagation constant about the angular frequency ω_0 as [7]:

$$\beta(\omega) = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2}\beta_2(\omega - \omega_0)^2 + \frac{1}{6}\beta_3(\omega - \omega_0)^3 + \cdots \quad (6.3)$$

Where, $\beta_1 = {}^{1}\!/_{v_g}$ (v_g is the group velocity), β_2 represents the dispersion of the group velocity, while β_3 is the third-order dispersion coefficient. The group velocity dispersion (GVD), β_2, is often related to the dispersion parameter D, and can be calculated by [8]:

$$D[ps/nm/km] = -\frac{\lambda}{c}\frac{d^2\,\mathrm{Re}[n_{eff}]}{d^2\lambda} = -\frac{2\pi c}{\lambda^2}\beta_2 \qquad (6.4)$$

If parameter D is negative, this is the normal dispersion regime where the red components of the pulse travel faster than the blue components. Similarly, if D is positive, is corresponds to the anomalous dispersion regime, where the red components of the pulse travel slower than the blue components [8]. When D = 0, which corresponds to the zero dispersion wavelength. The waveguide dispersion is very sensitive to the geometric distribution of the air holes in the photonic crystal cladding. Control of the chromatic dispersion in PCFs is an essential matter for the applications in the nonlinear optics, and dispersion compensation [6, 9]. The design parameters of these microstructured fibers (i.e., hole-sizes, hole to hole separation (pitch) and hole structure) strongly influence the waveguide dispersion and it is possible to design fibers with at dispersion profile and zero-dispersion wavelengths (ZDWs) in a wide range of the wavelengths ranging from visible to telecommunication bands. In order to achieve nearly-zero and ultra-flattened chromatic dispersion in PCFs, several intriguing designs such as hexagonal, octagonal, equiangular or hybrid structures have been proposed [5, 10 - 11]. However, in all mentioned structures, a small air hole in their center have been considered for further tuning the dispersion profile of these fibers. The presence of this small air hole results some drawbacks, such as increasing the confinement loss and making the dispersion characteristics very sensitive to the core even with large number of rings in the cladding [7, 12]. Moreover, the fabrication of these fiber with very small air holes (in nm scale) is very difficult to achieve and the synthesis of such structures is still a challenge [13].

6.2.3 Fiber nonlinearity

Fiber nonlinearities can be categorized in two ways. The first category of the fiber nonlinearities is known as a Kerr effects which is due to the nonlinear response of the material by intensity changes in the signal [7]. This results the nonlinearities such as self-phase modulation (SPM), in which the optical signal changes its own phase; cross-phase modulation (XPM), where one signal affects the phases of all others optical signals and four-wave mixing (FWM), where signals with different frequencies interact to produce mixing sidebands[14]. The second category corresponds to stimulated scattering processes, which is related to the interaction of the light waves with the optical photons of the fiber [15]. This produces the stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) phenomena. Fiber nonlinearities have different influences on the communication systems. The SPM, for instance, changes the dispersion behavior in high bit-rate transmission systems [16]; the XPM, SRS, and SBS decreasing the signal to noise ratio; the SRS and FWM increasing the crosstalk between different WDM channels in long haul optical systems [17]. The parameter that is generally used to measuring the fiber nonlinearities is known as the non-linear coefficient (γ) and is defined as [7],

$$\gamma = {2\pi n_2}/{\lambda A_{eff}} \qquad (6.5)$$

Where, n_2 the nonlinear refractive index of the material is, λ is the wavelength, and A_{eff} the effective mode area, which is determined by the PCF design and given by [18]:

$$A_{eff} = \frac{n_2 \left[E_t(x,y).E_t^*(x,y)dxdy\right]^2}{\tilde{n}_2(x,y)\left[E_t(x,y).E_t^*(x,y)dxdy\right]^2 dxdy} \qquad (6.6)$$

Where, $\tilde{n}_2(x,y)$ is the nonlinear refractive index of the material positioned at (x, y). Generally PCFs are made from the pure silica with a nonlinearity of $n_2 = 2.2\times10^{-20}\, m^2/w$ [19]. The fiber nonlinearity can be enhanced by reducing the effective area or/and by using a glass with higher refractive index n2 than the silica glass. The highly nonlinear glasses such as lead silicate glass [20], tellurite glass [21], and bismuth glass [22] with higher nonlinear refractive index at least one order of magnitude than the silica have been reported up to date.

6.2.4 Some applications of PCFs

PCFs with unusual guiding mechanism and novel properties can be used in variety of applications. Here, I briefly explained two main application of them in the area of the telecommunication.

6.2.4.1 Supercontinuum generation

The generation of supercontinuum was first observed in 1970 by Alfano and Shapiro [23] is one of the main applications of the index guiding PCFs. Supercontinuum generation in optical fiber involves the interplay between nonlinear and linear effects that occur during the propagation of an optical field (pulsed or continuous wave) in a fiber waveguide [23]. The supercontinuum generation (SCG) phenomenon corresponds to an extremely wide spectrum which is the result from the combined action of several nonlinear effects, such as SPM, XPM, higher-order soliton fission, SSFS, SRS, and FWM, together with the fiber dispersive properties [24]. However, the generation of a flat and wide spectrum is directly dependent on parameters such as materials nonlinearity, the length of the fiber, pump power and pumped wavelengths [25, 26]. PCFs allow one to generate a supercontinuum extending in an extremely large range from visible to the near infra-red, including anomalous and normal regimes. Another advantage of using PCFs for supercontinuum generation is the small effective area of the mode, leading to high intensities in the fibers. Moreover, nonlinear processes involved in the supercontinuum generation can be significant even for relatively low pulse energies on the order of Pico-Joule for femtosecond pulses [27]. In this case, the nonlinear effects suffered by very short higher order solitons propagating on these fibers originate a very broad output spectrum that has many applications such as optical metrology [28], broadband optical fiber communications [29], optical coherence tomography, dispersion measurement and ultra-short pulse generation [30] or as the source of the WDM systems [31].

6.2.4.2 All optical wavelength convertor

All-optical signal processing is a key technology for high-speed optical networks. All-optical signal processing seems to be the only technology that in a near future can provide ultrahigh-speed operation at data rates of 100 Gbit/s or higher [32]. The functions that are expected to be possible to perform using all-optical signal processing include optical regeneration, wavelength conversion, optical amplification, optical routing and signal monitoring [32 - 34]. Several proposals to implement all-optical signal processing have been presented in the literature based the third order nonlinear response of optical fibers [35, 36]. Most of these proposals are based on self and cross-phase modulation, which are inherently intensity dependent. However, in high-speed optical communication system (≥40 Gbit/s) signals tend to use phase modulation, which makes most of the proposed regenerators useless [32]. However, there is another third order nonlinear effect, the four-wave mixing process (FWM), that is phase dependent and can be used to process phase modulated signals [35]. However, to make use of this nonlinear phenomenon in optical signal processing a suitable fiber is required. Index guiding PCFs provide a good medium for DWDM wavelength conversion due to its high nonlinear coefficient, dispersion flattened profile, and high stimulated Brillouin scattering (SBS) threshold [32]. As a result, the length of optical fiber can be greatly reduced and the bandwidth and the efficiency of wavelength conversion can be improved [37].

6.3 Proposed PCFs structures

As mentioned in previous section, the nonlinearity of the PCFs can be further enhanced by using some of the following options: i) reduce the core diameter below one micron; ii) design the fiber microstructure or iii) use some highly nonlinear materials to make the fiber, namely lead-silicate, bismuth oxide, tellurite, and chalcogenide glasses. Using such highly nonlinear fibers (HNLFs), the required fiber length for nonlinear processing can be dramatically reduced to the order of centimeters, representing an improvement by several orders of magnitude in comparison with the use of conventional silica fiber. In this section, two novel structures for PCFs is discussed and obtained results are compared with other results in the literature. As a first design, the equiangular spiral design is optimized to obtain nearly zero dispersion and low confinement loss in telecommunication band. Secondly, the most widely used structure for PCFs (Hexagonal) structure is optimized with different material composition in order to obtain the high nonlinearity, low confinement loss and zero dispersion in 1.55 μm wavelength for application in telecommunication.

6.3.1 Equiangular Spiral Photonic Crystal Fiber design

Spiral shapes can be found in various nature phenomena, such as in shells of snails, galaxies and nautilus. The first spiral design for the PCFs was proposed by Arti Agrawal et al [38]. The model proposed by this group in Southampton university with lead silica glasses presents a very high nonlinear coefficient at 1064 nm and 1550 nm, namely, γ =5250 $W^{-1}Km^{-1}$ and 2150 $W^{-1}Km^{-1}$, respectively, and a low dispersion at 1060 nm, i.e., 0.795 ps/nm.km. We study an equiangular spiral photonic crystal fiber (ES-PCF) made of SF57 with a structure consisting of holes with different diameter and including a first ring, which will be optimized to obtain at dispersion at the telecommunications wavelength window. Our optimum design has a dispersion profile with two zeroes located at 1550nm and 1.760nm, with an ultra-flattened dispersion at a wide range of wavelengths in the C and L telecom bands. It also exhibits a low confinement loss and a high nonlinear coefficient at the region of interest.

6.3.1.1 Model definition

Fig. 6.1 shows the proposed ES-PCF, which consists of a soft glass (SF57) fiber with air holes in the cladding that are positioned in nine arms and five rings according to the ES equation that, in polar coordinates, (r, φ), is $r = b\exp(\varphi\cot(\alpha))$ [39], where b is closely associated with radial distance and parameter α represents the constant angle that the radial direction at a given point of the ES curve makes with the tangent to that point. Another ring of smaller air holes is introduced closer to the fiber core, positioned at a distance of the r_0 from the center. The angular separation between holes of the same ring and in consecutive spiral arms is $\theta = \pi / N_{arms}$. To avoid overlap between adjacent holes, the value of should be carefully chosen. Here, we considered $\alpha = (2N_{arms} - 5)/(N_{arms} - 2)$, which works well for our hole diameter and parameter b. In our study, we considered that the air holes in the outer rings of the ES have gradually increasing diameters (d_i), from d_1 = 0.45 µm to d_5 = 0.85 µm with a step of 0.10 µm. Furthermore, the position of these outer rings can be written as $r_i = k(i-1)r_1$, where $i = 2,..,5$, $r_1 = 1.1$ µm, and k = 1.227 . On the other hand, the value of r_0 and the diameter of the holes in the first ring will be optimized to obtain the desired optical properties for this PCF. The proposed structure also includes a very small air hole of radius r_c , which is used to further tune the dispersion

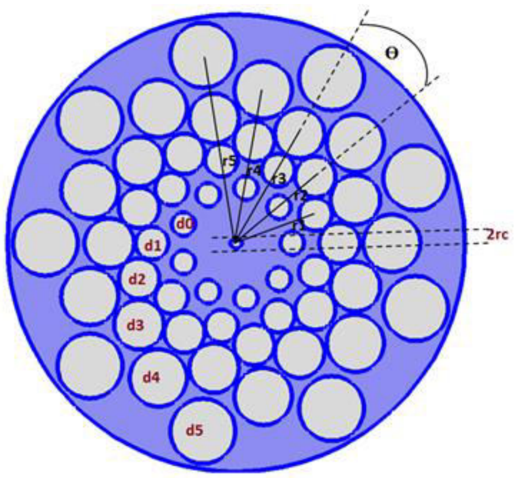

Figure 6.1: Cross-section of the proposed ES design with nine arms and five rings and an additional inner ring.

The guided modes supported by this structure, as well as their effective refractive indexes, were obtained as a function of wavelength by solving the wave equation using a commercial COMSOL Multiphysics software [40]. Once the modes and the modal effective index n_{eff} are obtained, by solving an eigenvalue problem drawn from the Maxwells equations, the dispersion (D), confinement loss (CL) and effective area (A_{eff}) can be deduced. Note that the nonlinear refractive index for SF57 and air is given by $4.1\times10^{-19}(m^2/w)$ and $3\times10^{-23}(m^2/w)$ respectively [17, 31].Our results have taken in account the material dispersion defined by the Sellmeier equation using the coefficients given for the commercially available lead silicate glass (Schott SF57) [31].

6.3.1.2 Simulation results

We started by studying the effect of adding an inner ring to a structure consisting of five rings. The air holes in the inner ring have diameter d_0 = 0.3μm and are positioned at a distance r_0 = 0.75μm from the center. An additional central hole with diameter r_c = 20 nm was also considered. We obtained the dispersion profile, the confinement loss, and the nonlinearity for each case and compared our results with results presented by Agrawal Team [38]. As shown in Fig.6.2, the dispersion profile of the proposed design with nine arms and five rings is flatter and closer to zero than the result presented in refs. [38, 39], obtained with seven arms and four rings, for the wavelengths at the telecommunications window region. Moreover, the result in this figure indicates that the design with an inner ring exhibits a flatter dispersion. On the other hand, the confinement loss curves represented in Fig.6.3 clearly show that the loss with our design is significantly lower than that reported results. Furthermore, the structure with inner ring holes causes better field confinement. The confinement losses increase with the wavelength, implying, as expected, that the modes for longer wavelengths are less confined in the core. In turn, this also affects the nonlinear coefficient and causes its decrease with the wavelength, as can be observed in Fig.6.4. The nonlinear coefficient for the structure with an inner ring is higher than the one for the structure without such ring. Our simulation results also showed that the nonlinearity remains approximately constant regardless of the number of rings used in the outer cladding. This suggests that the effective mode area of a structure with three or more outer rings is independent of the number of rings.

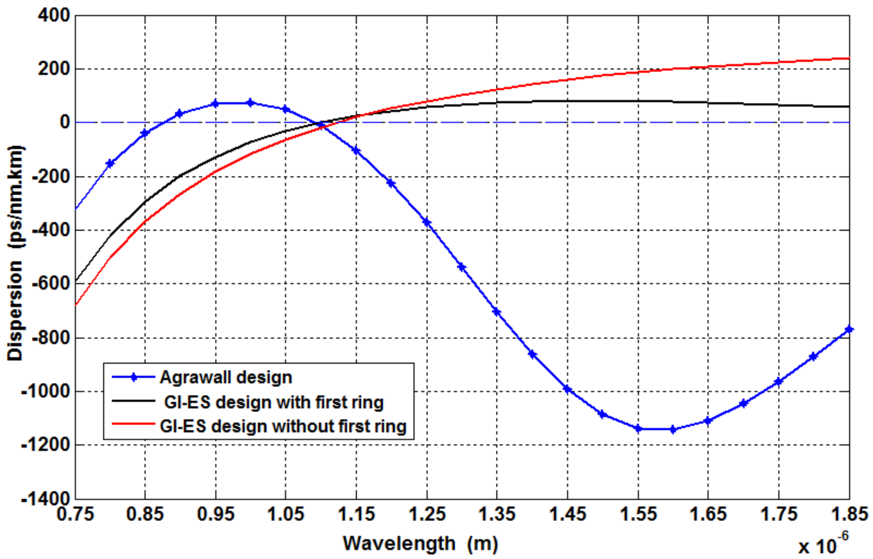

Figure 6.2: Dispersion profile as a function of wavelength for different structures.

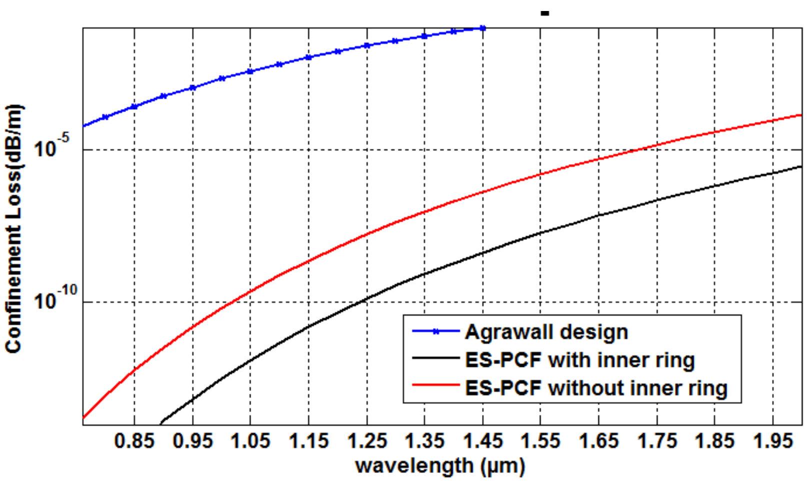

Figure 6.3: Confinement loss changes for different structures.

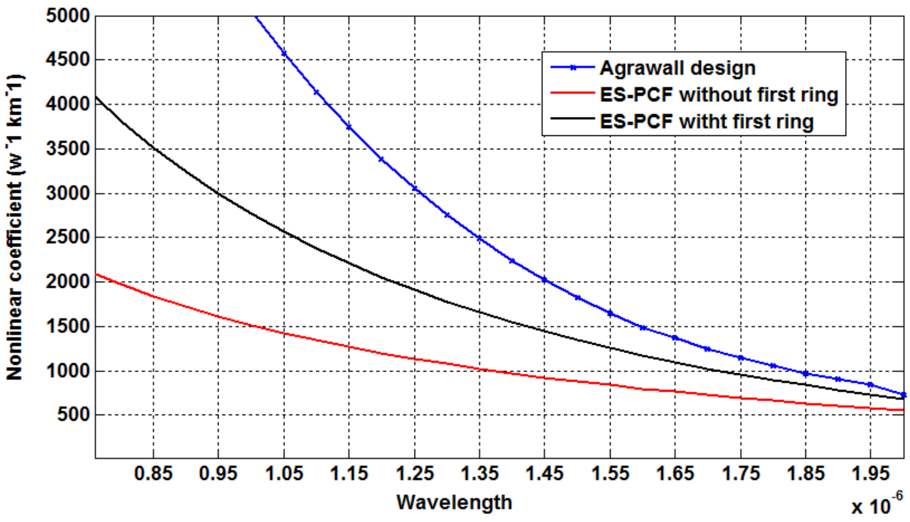

Figure 6.4: Nonlinearity changes as a function of the wavelength for different structures.

The choice of ES-PCF structure, which has nine arms in five rings with unequal diameter for air holes and an inner ring, provides better control of dispersion curve, high nonlinearity, and lower confinement loss. The fact that the curves corresponding to the structures with and without the inner ring are quite different suggests that the careful adjustment of the geometric parameters of the inner ring will allow an optimization of the equiangular PCF properties. Therefore, in what follows, the influence of r_0 and d_0 in the optical properties of this PCF will be studied. Fig.6.5 shows the wavelength dependence of the dispersion for different values of the parameter r_0 when d_0 = 0.30 µm and r_c = 0.075 µm. The simulation results show that, under these conditions, as the r_0 increases the dispersion increases and the zero dispersion shifts from 1.55µm to lower wavelengths. For r_0 = 0.735µm, the dispersion curve attains values close to zero at a large wavelength band centered at 1.55µm. We then proceed by considering the inner ring radius to have the optimum value r_0 = 0.735µm and investigate the effect of varying the air hole size in that ring. Fig.6.6 presents the dispersion profiles in this case, r_0 = 0.735µm and r_c =0.075µm, for various values of d_0. From this figures, it can be observed that the increase of the air holes diameter in the inner ring is associated with the decrease of the dispersion at wavelengths around 1.55µm . Furthermore, for the air hole diameter d_0=0.31µm , the dispersion curve is closer to zero at wavelengths in the telecommunication window around.

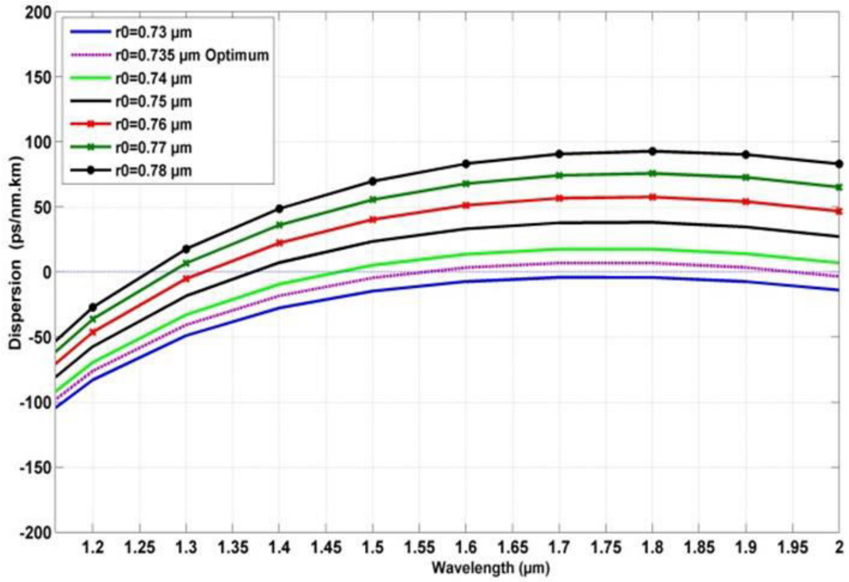

Figure 6.5: Dispersion curves of the ES-PCF for different values of r_0 when d_0 =0.30 µm and r_c =0.075 µm.

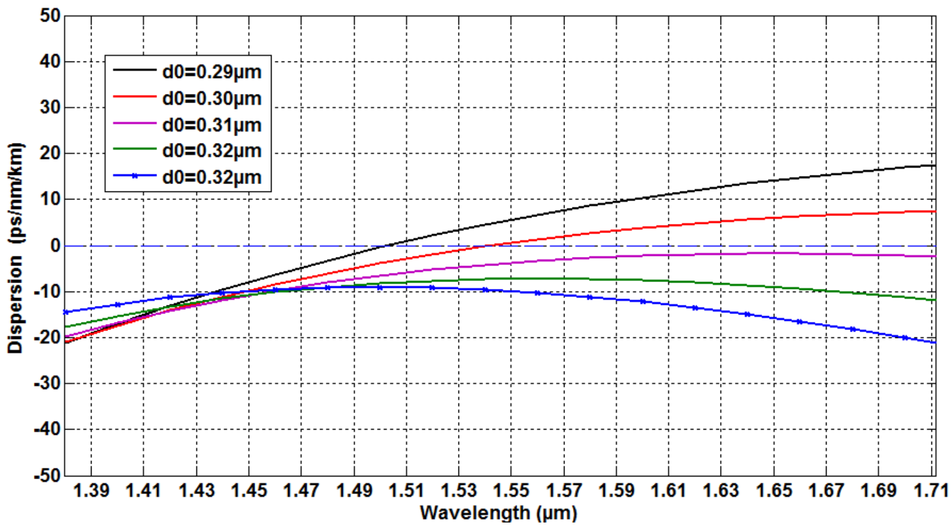

Figure 6.6: Dispersion curves for different values of d_0 when r_0 =0.735 µm and r_c =0.075 µm.

As a final step in the optimization process, we took the inner ring radius and holes diameter to attain the optimum values mentioned above and computed the dispersion profiles for different central hole radius. Our results, depicted in Fig.6.7, shows that increasing the central hole radius reduces the values of both the anomalous dispersion and dispersion slope near the zero dispersion wavelength. However, it also decreases the anomalous dispersion bandwidth, as can be observed in this figure. The best dispersion profile is obtained with the value of r_c =0.0735 µm , which exhibits a dispersion profile with two zeros nearly at 1.55 and 1.76 µm , and ultra-at dispersion at the wavelength range of 1.51 to 1.81µm (300nm band) with a maximum value of $\pm$ 2ps/nm.km. Moreover, for these optimal parameters, values of the confinement loss below 0.0031 dB/km were observed in that wavelength region.

We also obtained a nonlinear coefficient of 1285 $W^{-1}Km^{-1}$ at 1.55 µm. Fig. 6.8 presents the electric field profile for the chosen parameters at 1.55 µm, and shows that in this case the mode is well confined within the area defined by the first ring.

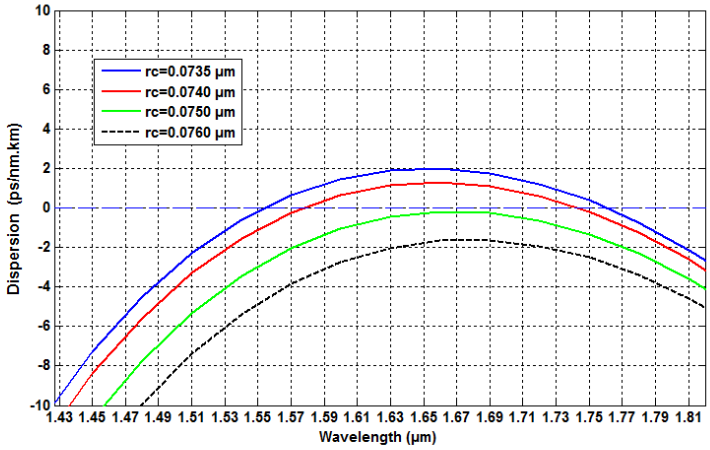

Figure 6.7: Dispersion profile for optimum d_0 and r_0 varying the central hole r_c =0.075 µm.

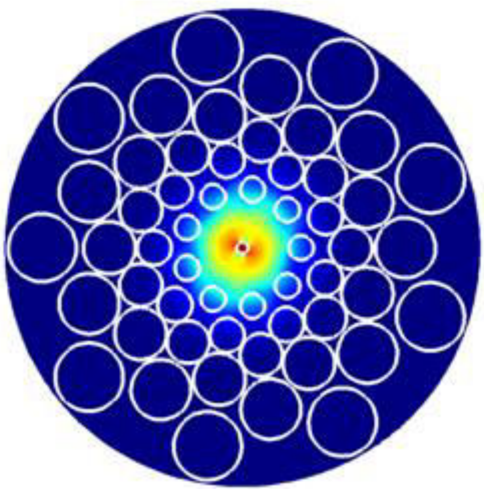

Figure 6.8: Electric field profile of the fundamental mode at 1.55 µm

6.3.2 Ultra-fattened dispersion multi-materials using hexagonal structure

The hexagonal structures due to simplicity and a few parameters for optimization are widely uses in the scientific works [19]. A large number of hexagonal structure PCFs with at dispersion, including hexagonal PCF with defected a central hole [23], doubled cladding PCF[27], PCF with several different air holes diameter[33] have been reported up to date. In order to further tune the dispersion profile of these fibers, a small air hole in their center has been considered. However, this presents some drawbacks, such as increasing the confinement loss and making the dispersion characteristics very sensitive to the core even with large number of rings in the cladding. Moreover, the existence of such a very small air hole requires some improvement in the fabrication process. In this work, we employ the index-guiding PCF with hexagonal structure without using a central hole which is made with different materials, namely, pure silica, lead silica (Schott SF57) and tellurite glasses. Based on the relatively simple structure, the geometry of the waveguides are optimized for each material, in order to obtain zero dispersion wavelengths and low dispersion slope, as well as high nonlinearity and low confinement loss at the telecommunication window. Our simulation results indicate that by adjusting a few parameters in the hexagonal structure, such as first ring holes diameter or air filling fraction, the proposed design could obtain at dispersion in a wide range of wavelengths with high non-linearity and low confinement loss. The optimized structure is numerically analyzed by using the finite element method (FEM). The boundary condition is treated with scattering boundary condition to minimize the reflections at the boundary and thus simulate an unbounded region. The materials dispersion given by Sellmeier equation is directly included in calculation by defining $n^2 = 1 + \sum_{i=1}^{i=L} \left[A_i \lambda^2 / \lambda^2 - L_i^2 \right]$, where the fitting coefficient A_i and L_i for selected glasses are listed in table 6.1.

Material	Pure Silica		Lead Silica		Tellurite	
n_2	2.2×10^{-20}		4.1×10^{-19}		5.8×10^{-19}	
	A_i	L_i	A_i	L_i	A_i	L_i
$i=1$	10.6961663	0.004679	1.81651371	0.1199	1.67189	0.0004665
$i=2$	0.4079426	0.01351	0.42889361	0.2435	1.34862	0.0574608
$i=3$	0.8974794	97.93	1.07186278	11.0191	0.62186	46.72542736

Table 6.1: Nonlinear coefficient and sellemeier coefficient for the selected glasses [15, 23]

6.3.2.1 Modal Design and simulation results

The cross-section of proposed PCF design is shown in Fig.6.9. The cladding consists of air holes embedded in selective glasses and arranged in a triangular array, with the hole to hole separation (pitch) is Λ. The air-hole diameter on the first ring is d_1, while the diameter of air-holes in the outer ring is d .The full vector finite element method with scattering boundary condition is used to obtain the optical properties of proposed design..

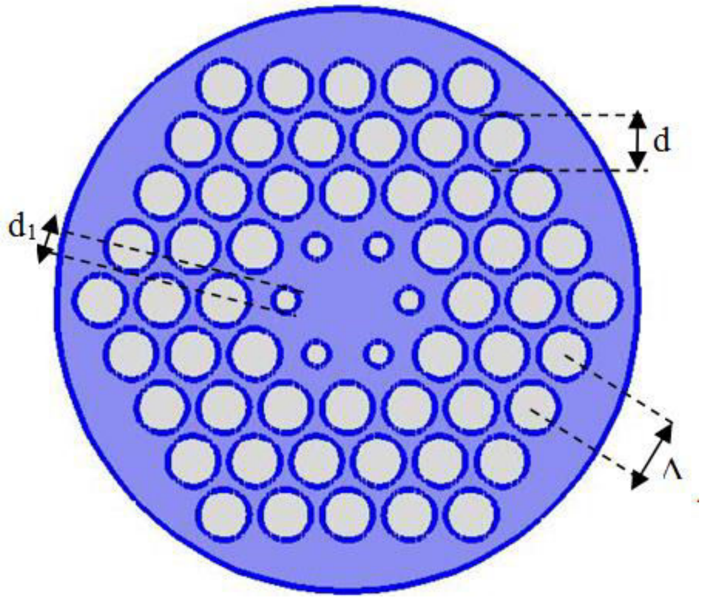

Figure 6.9: Cross-section of the proposed Hexagonal design

The structure of the proposed PCF is optimized with selected nonlinear glasses in order to obtain nearly zero dispersion at 1.55 μm and flattened dispersion in the wide range of the wavelengths in the telecommunication window. We start our optimization by using a pure silica material at the cladding of the PCF. We optimized the parameters in a simple way. First, we choose a pitch value Λ=1μm and set the first ring holes diameter to values to $d_1 = 0.3d$ changing the air-filling fraction value d/Λ and choosing the flattened dispersion curve at telecommunication window. Second, we scaled the first rings air-holes value until zero dispersion characteristic is found around the 1.55μm wavelength. Fig.6.10 shows dispersion curves of the proposed PCF, when the d/Λ=0.7, the dispersion curve of the PCF is found wavelength ranging from 1.4 to 1.9μm.

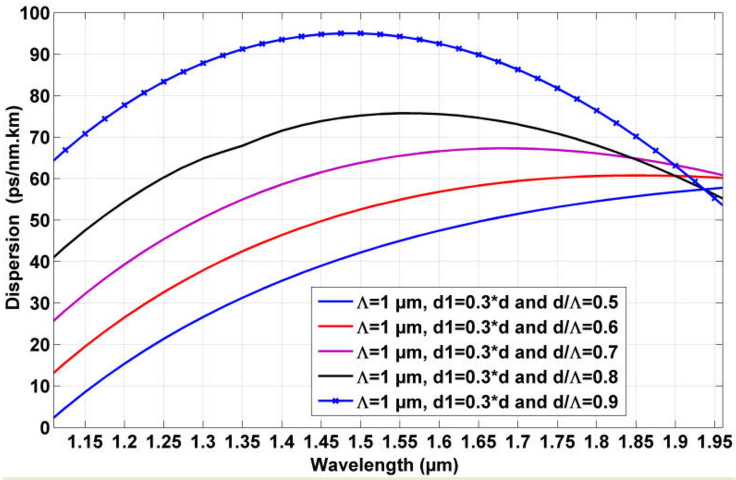

Figure 6.10: Dispersion curve changes as a function of the d/Λ.

In Fig. 6.11 we plot the dispersion curves with the outer rings has Λ=1μm and d/Λ=0.7 varying the size of the d_1. It can be seen the increment in the size of the air-hole diameters in the first ring d_1 in the cladding, down-shifts the waveguide dispersion curves. As it can be seen, when t $d_1 = 0.49 \times d$, dispersion curve indicates nearly zero and flat dispersion at the wide range of wavelengths at telecommunication window. The result with optimum parameters with wider zoom can be seen in the Fig.6.12, where this structure indicates two nearly zero dispersion located at 1.55 and 1.76μm and at dispersion with the maximum value of 1 ps/nm.km at wavelength ranging from 1.5 to 1.86μm (360 nm band).

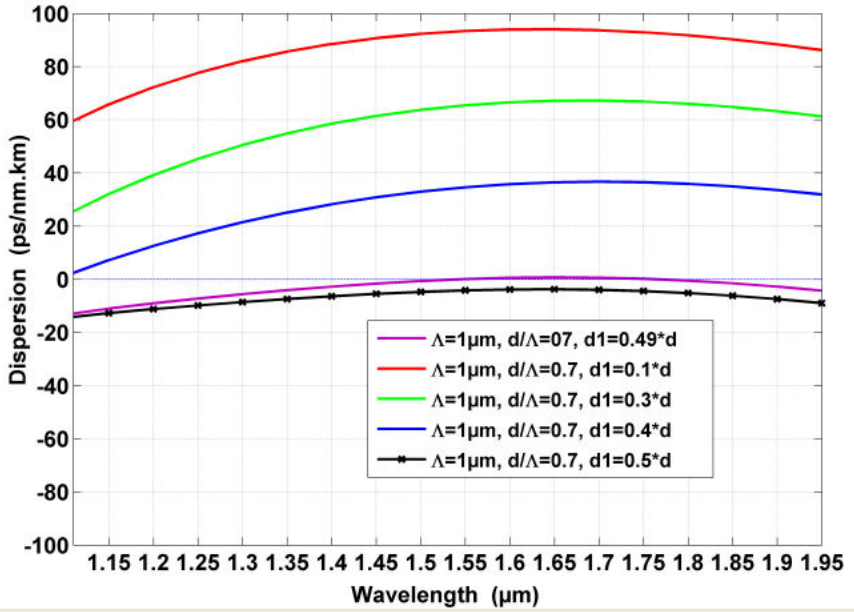

Figure 6.11: Dispersion curve by varying the first ring holes diameter (d_1).

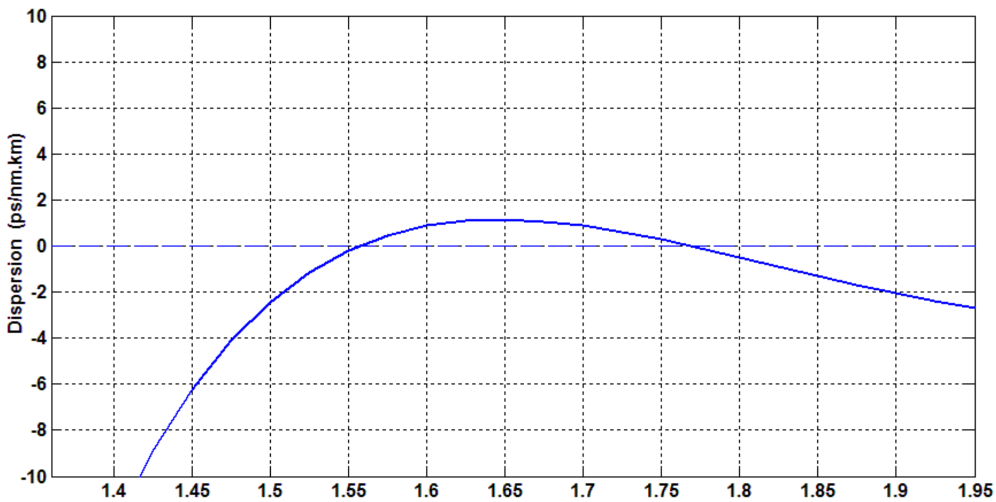

Figure 6.12: Optimum design with Λ=1μm , d/Λ=0.7 and $d_1 = 0.49 \times d$ (Pure silica) .

The same optimization mechanism has applied for the proposed structure with lead silicate and tellurite glasses. The dispersion profile changes results for lead silicate and tellurite glasses are depicted in Fig.6.13 and Fig.6.14 respectively. Form the observation of the Fig.6.13, we can see the proposed lead silica PCF with optimum value of d/Λ=0.969, $d_1 = 0.499 \times d$ and $d = 1\mu m$ can tailor nearly zero dispersion at wavelengths 1.5 and 1.55μm with ultra-flattened dispersion in a wide range of the wavelengths from 1.45 to 1.95 μm with the maximum value of 0.5ps/nm.km.

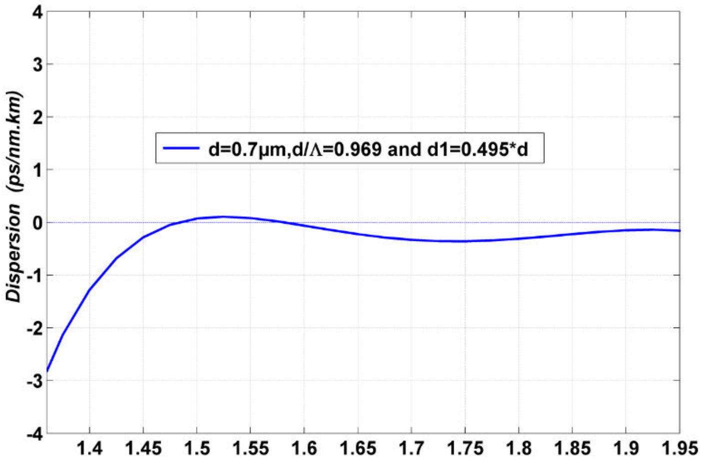

Figure 6.13: Variation of the chromatic dispersion as a function of the wavelength with the optimum design (lead silica glass).

Figure 6.14 illustrates the optical properties of the PCF with tellurite glass, for which the optimum parameters are d= 0.7 μm, and d/Λ=0.921. The simulation result shows a flat dispersion with the slope of ± 2 ps/nm.km at wavelengths ranging from 1.5 to 1.9 μm (400nm band) with two zero dispersion wavelengths at 1.55 and 1.75μm.

The nonlinear coefficient of the optimum design as a function of the wavelength for the selective glasses is shown in the Fig.6.15. It is obvious from that figure, as we expected, among the three selected glasses in our work, the teluritte glass which has the highest nonlinear refractive index exhibits the highest nonlinearity. The dispersion, confinement loss obtained from the three different glasses at the 1.55 μm wavelength are shown in in Fig.6.16.

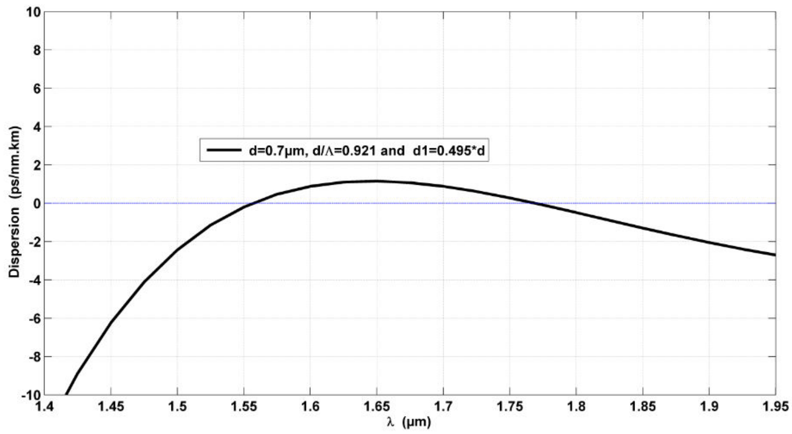

Figure 6.14: Variation of the chromatic dispersion as a function of the wavelength with the optimum design (Tellurite glass).

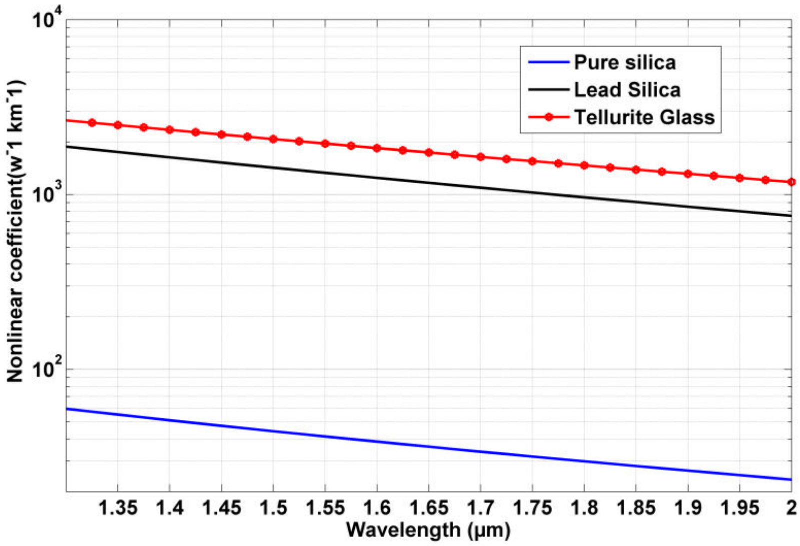

Figure 6.15: Nonlinearity changes with three different materials with optimum parameters

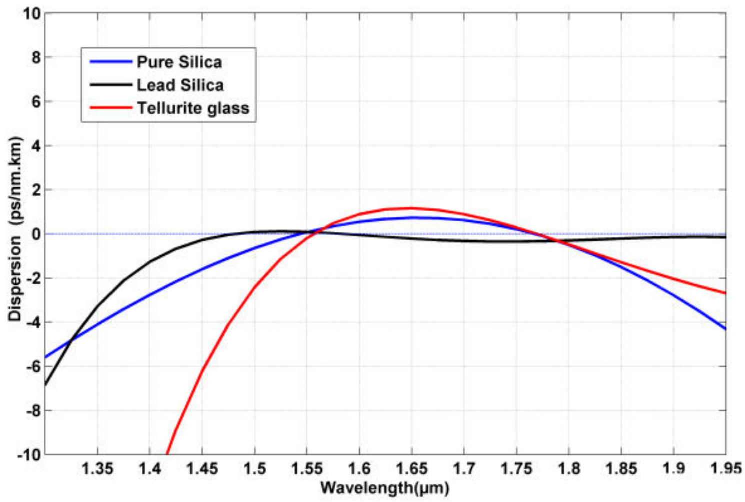

Figure 6.16: Dispersion curve with three different materials with optimum parameters.

6.4 Summary

The structural parameters of the PCF with different structures and materials are optimized and the numerical analyses have demonstrated the fiber design prominent for applications in dispersion control and nonlinear optical systems in the area of the telecommunication band. A novel design of an ES-PCF has been proposed. The effect of variation of the PCF geometry, including the influence of inner air hole diameter, central hole diameter, number of rings and distance from the center, in terms of the dispersion, nonlinearity and confinement loss has been investigated. The results show that lower values of dispersion and confinement loss can be obtained by considering the existence of an inner ring with smaller air holes and a small central hole. Our ES-PCF model with lead silica can tailor nearly zero dispersion at 1.55 μm and has ultra-flattened dispersion at wavelength at the C, L telecommunication band, while also exhibiting very low confinement loss and a high nonlinear coefficient.

Our hexagonal PCF with different glasses can tailor nearly zero dispersion at 1.55μm and has at dispersion at wavelength at C, L telecommunication band, while also exhibiting very low confinement loss and a high nonlinear coefficient. The main advantage of the proposed structure is that this design procedure is very effective and straightforward, depending on a few geometrical parameters for optimizing the optical properties of these PCFs. On the other hand, due to absence of the central hole in our design, this design can be use by current fabrication method.

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7 Chapter 7 Conclusions and Future works

7.1 Conclusions

Nowadays, an exponential increase of the internet traffics with new developments such as video on demand, High Definition (HD) and three-Dimension (3D) television (TV), cloud computing, video conferences, etc. has been proposed new challenges for the next generation high bandwidth demand required for home access networks. Fiber-to-the-home (FTTH) services that interconnect homes with a glass optical fiber (GOF) cables to the core optical network in advanced countries, are well established.

Currently, the last few miles in local access network is based on a mixture of separate networks, each optimized to provide a particular set of services with widely differing needs regarding, e.g., bandwidth, quality of service, and reliability. These multiple infrastructures for in-home networks cause a complicated consumer experience, expensive maintenance costs, and high-power consumption.

Optical fiber is optimally suited to meet this demand where, it can handle a wide variety of services in a single network infrastructure. In short distance applications like in home networks, the plastic optical fiber (POF) offers an attractive medium, which provides ease of installation and termination, low cost components, simplicity in termination and installation and offers large flexibility and ductility in compare to the "classic" single/multimode glass optical fibers and /or CAT development. The big differences of the POFs compared to silica-based fibers are mainly the core diameter and material, which lead to high attenuation and small bandwidth. Within the family of the polymer optical fibers, big differences arise when the PMMA based POFs are compared with the perfluorinated one. The first fiber is a low cost solution with a core diameter of 1mm. The large core size of these type of the POFs support a very large number of modes that propagate through different paths inside the fiber core, causing modal dispersion.

The second one which is known as perfluorinated graded index POF (PF-GI-POF) is a competitor to the silica based MMF with core diameters of up to 120 μm. The PF-GI-POF offers higher bandwidth, lower attenuation within the infrared region (IR) spectra and in particular both at 850 nm and 1,300 nm wavelength. Moreover, PF-GI-POFs are more compatible to the low cost and low power consumption multimode vertical cavity surface emitting lasers (VCSELs) at 850nm wavelength, where these types of the fiber has their lower attenuation loss in this region.

This thesis has highlighted the capacities of the PF-GI-POF able to support the transmission of the high data rate baseband standard (up to 10 Gbps). The viability of this multimode fiber in ROF and WDM techniques for home network application is also analyzed. Commercially available multimode transceivers on the market use simple OOK modulation format. Experimental studies over this modulation have shown that the fiber length is restricted to 100 m owing to the multimode behavior of the PFGI-POF which limits the fiber modal bandwidth. The bandwidth limitation due to the modal dispersion in a PF-GI-POF transmission system can be counteracted by using electrical equalizers and/or using more advanced multi-level modulation schemes.

For the simplicity, easiness and less power consumption, PAM-4 modulation and simple FFE and DFE equalization techniques is used for simulation studies in this thesis. The simulation results demonstrated that combination of the DFE equalizer with NRZ modulation, transmission length can be increased to 300m long at data rate of 10Gbps for both NRZ and PAM-4 modulation. However, the PAM-4 modulation needs 4 dB more receiver power than NRZ, at the same bit-rate.

In this thesis the use of the multilevel modulation in combination with receiver equalization achieved very good results in terms of data rate and link length over PF-GI-POFs. However, the addition of the digital signal processing schemes like PAM-4 and/or digital equalizations in order to make short reach home network systems more robust and achieve higher data rate might be very interesting approach from the research point of view, but does drive the cost and complexity and power consumption of the such system up. The complexity of such techniques should be very well chosen to optimize the key factors such as price, energy efficiency, ease of the use, quality of the services (QoS) and transmission speed to be competitive solution in the global market.

After exploiting the capabilities of the POF systems in a single channel, the next step was to increase the capacity of an individual POF is to use multiple channels over a single fiber what is well known as wavelength division multiplexing (WDM). Applying WDM can further enhance the transmission capacity via POF systems. Nowadays, WDM is well-established in the infrared transmission windows for silica optical fibers, but this technique needs to be adapted to Infrared region for POFs due to their spectral attenuation behavior. The key element for WDM system is a fiber Bragg grating, which is needed to filter and separate the incoming signal for receiver. The capabilities of novel POFBG devices to be compatible with WDM topologies for both sensing and communication schemes have been addressed. A four channel WDM over PF-GIPOF deployment is studied showing that its total achievable capacity can overcome the bit-rate limitation of the POFs.

Although the utilization of WDM multiplex technology over POF offers higher performance than existing technologies, the economic analysis has shown 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.

In chapter 5 the transmission of RF signals in conventional DRoF systems to deliver digital baseband for both wire and wireless users in home network has been presented and evaluated. Experimental results show that the system has a linear behavior in terms of EVM until a certain optical power received, and the greater the number of bits of resolution. The experiment results show that with the coexistence of 2km of single mode fiber (SMF) and 50 m of the GI-POF, 1.25 Gb/s baseband signal with 16 quadrature amplitude modulation (QAM) can be accommodated in our proposed scheme. Moreover, the proposed architecture is economically competitive for either upgrading installed systems as well as for new deployments.

Chapter 6 of this PhD study is focused on the applications of the photonic crystal fibers in the telecommunication area. Analytical and accurate numerical tools is employed to study the index guiding PCFs. Index guiding PCFs made of different highly nonlinear materials with two novel structures were optimized in order to achieve ultra-flat dispersion, high nonlinearity and low confinement loss over a broad range of wavelengths in the perspective of their usage in telecommunication applications. Numerical investigations have been shown that by carefully designing the size, shape, and spacing of the air holes of a microstructured fiber, the total dispersion can be considerably modified. Their nonlinearity can be enhanced by using materials with a high nonlinear refractive index.

7.2 Future research directions

The most obvious future research direction of this dissertation is the continuation of the primary goal of this research i.e. improvement of the POF links by enhancing the bandwidth-distance while reducing the system complexity and cost. In this thesis, we have designed the multi-level modulation in combination with equalization scheme, 10 Gb/s data can reach to the 300m of the POF. However, realization of a commercial product requires robust performance with improvement in the power budget which can be achieved by improving the receiver sensitivity. So, the main challenge lies in the design of the new receivers with high sensitivity.

For multichannel transmission over POFs, an investigation branch might be the electronic side of these system and how would be that “optical routers” which every user would have in his/her house, paying attention in conversion between different physical layers, and modulation schemes. Moreover, measure and characterize the system from a more realistic scenario by taking to account the nonlinear phenomena such as four wave mixing (FWM) or kerr nonlinear effects on the system.

The question of the weather or not the POF would be the future technology in home networks and can be seen in European houses for next 5-10 years cannot be answered directly. From the research point of view, it depends on the success of joint co-operations between major European companies and universities, such as the POF-ALL projects. The POF -ALL and POF-PLUS projects had a lot of influence on the POF developments.

Regarding the digitalized radio over fiber the analysis of the non-linear phenomena associated with propagation in the fiber is still a challenge. Simulation and experimental study to test the impact of the different intermediate frequency as well as the impact of the electrical filter on the system could be a future direction.

We have experimentally proved that with the coexistence of 20km of single mode fiber (SMF) and, 1.25 Gb/s baseband signal with 16 quadrature amplitude modulation (QAM) can be accommodated in 50 m of the GI-POF. Future direction could be the impact of other modulation schemes i.e. PAM modulation as a economically competitive for either upgrading the data rate and more importantly their role on the next generation mobile networks (5G).