Universidade de Aveiro
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Departamento de Electrónica, Telecomunicações e Informática (DETI)

Gabriel Gonçalves

Geração e distribuição de sinais ROF

Generation and distribution of ROF signals

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Electrónica e Telecomunicações, realizada sob a orientação científica do prof. Dr. Mário Lima e do prof. Dr. António Teixeira , ambos do Departamento de Electrónica, Telecomunicações e Informática e do Instituto de Telecomunicações da Universidade de Aveiro.

Este trabalho é dedicado aos meus pais, irmão, amigos e namorada, pelo incondicional apoio,

o júri

presidente

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palavras-chave

Radio sobre fibra (RoF), ultra-wide band (UWB), orthogonal frequency division multiplexing (OFDM), multiplicação de frequência.

resumo

O trabalho apresentado nesta dissertação incidiu no estudo de técnicas de geração e distribuição de sinais rádio sobre fibra (RoF).

Numa primeira fase estudaram-se os vários componentes associados ao canal óptico, para se perceber de que forma cada um deles afecta os sinais RoF que se propagam, e quais serão as principais limitações associadas.

No seguimento desse estudo inicial, efectuou-se trabalho experimental, de transmissão de sinais rádio (3G) sobre um sistema óptico mono-canal, para se observar e verificar os fenómenos limitativos identificados anteriormente.

Posteriormente, foi abordada a geração de sinais rádio por multiplicação de frequência no domínio óptico, com reduzido custo e complexidade, utilizando um modulador Mach-Zhender em regime não-linear, considerando diferentes formatos de modulação. As simulações efectuadas incidiram na optimização das topologias e parâmetros associados aos diferentes componentes envolvidos, em particular na emissão e recepção.

Este trabalho serviu de base ao apresentado no capítulo 5, em que se simulou e optimizou um cenário de distribuição em rede óptica passiva multi-canal, de sinais OFDM, compatíveis com UWB, gerados por multiplicação de frequência no domínio óptico.

keywords

Radio over Fiber (RoF), ultra-wide band (UWB), orthogonal frequency division multiplexing (OFDM), frequency multiplication.

abstract

The work presented in this dissertation focused on the study of techniques for the generation and distribution of radio signals over fiber (RoF).

Initially the various components associated to the optical channel were studied, to conclude how each of them affects the propagated RoF signals, and what are the key limitations associated.

Following this initial study, experimental work was carried out, the transmission of radio signals (3G) on a single-channel optical system was studied, to observe and verify the limiting phenomena identified earlier.

The next step was the generation of radio signals by frequency multiplication in the optical domain, with reduced cost and complexity, by using a Mach-Zehnder modulator in non-linear regime, considering different modulation formats. Several simulations were performed, focusing on optimizing topologies and parameters associated to the different components involved, especially in the transmitter and receiver.

The performed work was the basis to the concepts presented in Chapter 5, in which a distribution scenario involving a passive optical network with multi-channel OFDM signals, compatible with UWB, generated by frequency multiplication in the optical domain was simulated and optimized.

Contents

List of Figures

List of Acronyms

1G	First Generation
2G	Second Generation
3G	Third Generation
ADSL	Asymmetric Digital Subscriber Loop
AM	Amplitude Modulation
ASK	Amplitude Shift Keying
AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
CDMA	Code Division Multiple Access
CNR	Carrier-to-Noise Ratio
CO	Central Office
C.S	Carrier Suppressed
CW	Continuous Wave
dB	decibels
dBm	decibels milliwatt
DFB	Distributed Feedback
DSB	Double-Side Band
DWDM	Dense Wavelength Division Multiplexing
EVM	Error Vector Magnitude
FBG	Fiber Bragg Grating
FM	Frequency modulation
EDFA	Erbium Doped Fiber Amplifier
FWM	Four Wave Mixing

FWHM	Full Width at Half Maximum
Gbps	Gigabit per second
GHz	GigaHertz
GVD	Group Velocity Dispersion
GSM	Global System for Mobile communications
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IM	Intensity Modulation
IM-DD	Intensity Modulation with Direct Detection
ISI	Intersymbol Interference
LAN	Local Area Network
LO	Local Oscillator
LPF	Low-Pass Filter
Mbps	Megabit per second
MHz	Megahertz
MMF	Multi Mode Fiber
MZI	Mach-Zehnder Interferometer
MZM	Mach-Zehnder Modulator
NF	Noise Figure
OCS	Optical Carrier Suppression
OEO	Optic-Electric-Optic
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OFM	Optical Frequency Multiplication
OLT	Optical Line Terminal
ONT	Optical Network Termination

ONU	Optical Network Unit
OSNR	Optical Signal to Noise Ratio
OOK	ON-OFF Keying
PD	Photodetector
PMD	Polarization Mode Dispersion
PM	Phase Modulation
PON	Passive Optical Network
PRBS	Pseudo-Random Bit Sequence
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RAP	Radio Access Point
RAU	Radio Access Unit / Remote Antenna Unit
RHD	Remote Heterodyne Detection
RIN	Relative Intensity Noise
RF	Radio Frequency
RoF	Radio over Fiber
SBS	Stimulated Brillouin Scattering
SCM	Sub-Carrier Multiplexing
SF	Spreading Factor
SGM	Self Gain Modulation
SMF	Single Mode Fiber
SOA	Semiconductor Optical Amplifier
SPM	Self Phase Modulation
SRS	Stimulated Raman Scattering
SSB	Single Side Band
TDM	Time Division Multiplexing

UMTS	Universal Mobile Telecommunications System
VCSEL	Vertical Cavity Surface Emitting Laser diode
VPI	Virtual Photonics Inc. (simulation software manufacturer)
WAN	World Area Network
WDM	Wavelength Division Multiplexer
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
XGM	Cross Gain Modulation
XPM	Cross Phase Modulation

List of Symbols

a	Core radius
Aeff	Mode’s effective area
b	Normalized propagation constant
c	Light velocity of vacuum
C	Capacitor
D	Dispersion parameter
Dcro	Chromatic dispersion
Dm	Material dispersion
Dwg	Waveguide dispersion
E	Electric field vector
fosc	Oscillation frequency capable of being produced in the laser cavity
gth	Laser gain condition
h	Planck’s constant
Ip	Photodiode current
Id	Dark current
kB	Boltzmann’s constant
L	Inductor
Lf	Fiber length
Lc	Cavity length
m	Number of longitudinal modes
N	Number of propagating signals
n1	Core refractive index
n2	Cladding refractive index
nT	Refractive index
nL	Linear refractive index
nNL	Non-linear refractive index
P(x)	Optical power after propagating x km
P0	Optical power at the beginning of propagation
Pol	Induced polarization
PolL	Linear induced polarization

PolNL	Non-linear induced polarization
Po	Incident optical power
q	Electrical charge
R	Resistance
ri	Mirror’s reflectivity
T	Total delay
TR	Resistance temperature
Tc	Chip period
Tb	Bit period
V	Normalized frequency
vg	Group velocity
x	Propagation distance
R	Responsivity
λ0	Central wavelength
η	Quantum efficiency
φ	Phase rotation
ε0	Vacuum permittivity
σT	Differential group delay
γ	Non-linear coefficient
αp	Attenuation coefficient
αi	Material absorption coefficient
β	Phase propagation constant
ω	Frequency of the emitted signal
ω0	Central frequency of the emitted signal
Δ	Core-cladding refractive index difference
Δω	Frequency variation
ΔT	Delay variation
Δλ	Wavelength variation
Ω	Beat frequency

“Learn from yesterday, live for today, hope for tomorrow. The important thing is not to stop questioning.”

Albert Einstein,

Chapter 1. Introduction

1.1 Context

Wireless coverage of the end-user domain, be it outdoors or indoors (in-building), is intended to become an essential part of broadband communication networks. The increased demands for broadband services coupled with the proliferation of wireless devices are putting pressure on increasing wireless systems capacity. To achieve this, systems must operate at higher carrier frequencies, and cope with increased user population densities.

In order to offer integrated broadband services (combining voice, data, video, multimedia services, and new value added services), these systems will need to offer higher data transmission capacities well beyond the present-day standards of wireless systems. Wireless LAN (IEEE802.11a/b/g/n) offering up-to 600 Mbps [IEEE802.11, 2007], and 3G mobile networks (IMT2000/UMTS) offering up-to 2 Mbps [ETSI, 2008], are some of today’s main wireless standards, IEEE802.16, WiMAX is another standard aiming to bridge the last mile through mobile and fixed wireless access to the end user.

Radio waves are nowadays the most popular way to communicate, since they are used in the very front end of every user, as they provide an extremely important facility: mobility. On the other hand, the demand and increase of penetration of data and voice, has pushed the operators into several developments and strategies to enable full time, space and, whenever possible, bandwidth coverage to the users. This attitude leads the operators and their suppliers to find all types of technical solutions that can make the three aforementioned guidelines possible. Some of the challenges are, for example, to manage bandwidth in highly dense sporadic places, (commercial centres, shows, sport games) or to allow coverage in places where wave propagation is not easy. However higher operating frequencies (above 6 GHz) and smaller radio cells are needed for increased capacity per unit area, especially in in-door applications where due to building walls, high operating frequencies encounter tremendously high losses [Rahman, 2009]. To reduce the system installation and maintenance costs of such systems, it is imperative to make the radio antenna units as simple as possible. This may be achieved by consolidating signal processing functions at a centralised headend, through radio-over-fibre technology.

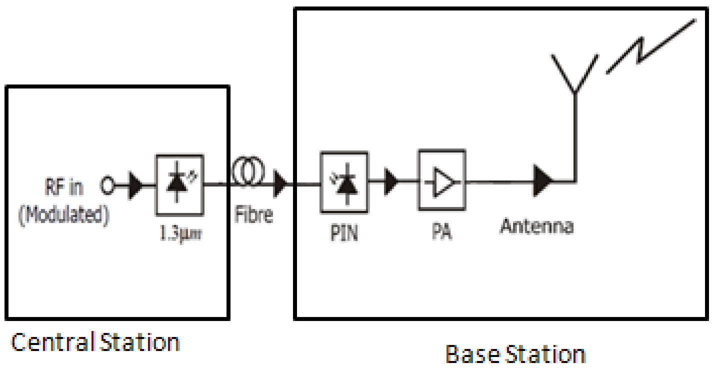


Figure 1.1- Simple RoF System

Primitive RoF systems using IM-DD (*Intensity Modulation Direct Detection*) such as the one depicted in figure 1.1 were primarily used to transport microwave signals, and to achieve mobility functions. Modulated microwave signals had to be available at the input end of the RoF system, which subsequently transported them over a distance to the RS as optical signals, being these signals re-generated and radiated by antennas. In addition to perceptions explained above, RoF systems of nowadays are designed to perform added radio-system functionalities besides transportation and mobility functions, such as modulation, signal processing, and frequency conversions (up-conversion and down-conversion). Considering a multifunctional RoF system, the required electrical signal at the input of the system depends on the technology and the functionality desired, the electrical signal used to modulate the optical source might be baseband data, modulated IF, or the actual RF signal to be distributed (figure 1.2).

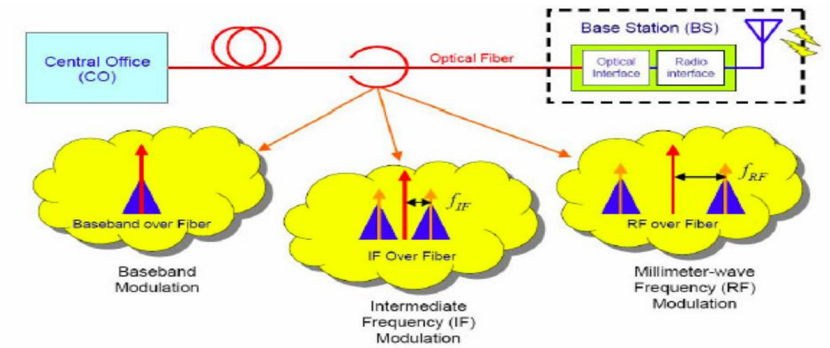


Figure 1.2 - Radio signal transport schemes for RoF systems [Opatic, 2007]

The resulting optical signal is then carried over the optical fibre link to the remote station, where the data is converted back into electrical form by the photo detector (which will be described later in). The generated electrical signal must meet the specifications required by the wireless application be it GSM, UMTS, WLAN or other. We have several possible approaches to transporting radio signals over optical fiber in RoF systems, which is classified based on the kinds of frequency bands (RF bands, IF baseband, baseband) transmitted over an optical fiber link. RoF analogue photonic links are typically multichannel in nature and require high power compared to digital schemes because of the increased carrier to noise ratio (CNR) requirements. The performance, including CNR and capacity, of RoF systems employing analogue optical links is limited by the noise of the various optical and electrical components in the link as well as by device nonlinearities, which introduce intermodulation and distortion products that create interference with other radio channels.

Momentarily RoF is probably the most straightforward radio signal distribution technology because the wireless signals are transported directly over the fiber at the radio carrier transmission frequency without the need for any subsequent frequency up or down conversion at the remote antenna BS. This configuration enables centralized control and remote monitoring of the radio signal distribution via the fiber backbone network and reduces the complexity of the BS implementation, but is susceptible to fiber chromatic dispersion that seriously limits the transmission distance. The wireless data obtained from the trunk network are modulated onto a number of lower intermediate frequency (IF) carriers, which are then combined to form a subcarrier multiplexed (SCM) signal. This SCM signal is up converted to the radio transmission frequency using a local oscillator (LO) source located at the CO and then modulated onto an optical carrier. At the remote BS, the analogue optical signal is detected, amplified, filtered, and directed to an antenna for free space transmission. Upstream radio transmission to the BS and subsequently back to the CO will require a mechanism for modulating an optical source located at the BS at the radio carrier frequency, and photo detection of this signal back at the CO.

IF signal transport schemes offer the advantage that the readily available mature microwave hardware can be utilized at the BS, although the requirement for frequency conversion at the BS increases the complexity of the BS architecture particularly as the frequency of the wireless application moves into the millimetre wave frequency region. The BS hardware now requires LOs and mixers for the frequency conversion processes, which may limit the ability to upgrade or reconfigure the radio network with the provision of additional radio channels or the implementation of required changes in RF frequency. IF radio signal transport allows transmission over low cost multimode fiber (MMF) and several commercial RoF products are based on the distribution of radio signals over MMF since many buildings have legacy optical fiber infrastructure networks based on multimode fibers.

The third technique that can be used to transport data carrying radio signals between the CO and the remote antenna BS in RoF systems is via a baseband over fiber approach as depicted in Figure 1.2. The radio information for the radio carriers is transported to the BS as a time division multiplexed (TDM) digital data stream. The individual data channels are then demultiplexed, up converted to IFs, before undergoing an additional frequency up conversion to the required radio frequency band via an LO located at the BS. Upstream signal transport via baseband over fiber can also be accomplished by down converting the received wireless carriers at the BS to the baseband before transmission back to the CO. As with IF over fiber, RoF systems based on baseband over fiber transport schemes can readily exploit the use of mature and reliable RF and digital hardware for signal processing at the CO and BS as well as low cost optoelectronic interfaces. The need for frequency conversion at the BS complicates the BS architecture design as the air interface frequency increases. The additional LO source and extensive signal processing hardware (frequency conversion and multiplexing and demultiplexing of signals from many users) in the antenna BS may also limit the upgradeability of the overall fiber radio system.

1.2 RoF: Motivation and advantages

Radio-over-fibre (RoF) technology has emerged as a cost effective approach for reducing radio system costs because it simplifies the remote antenna sites and enhances the sharing of expensive radio equipment located at appropriately sited (e.g. centrally located) Central Office (CO) as seen previously.

RoF systems use a technology by which microwave or millimetre waves (electrical) signals are distributed by means of optical components and techniques, it entails the use of optical fiber links to distribute RF signals from a central location (headend) to Remote Antenna Units (RAUs). A RoF system consists of two stations, central offices (CO) and a remote station (RS) connected by an optical fiber link or network. For example, if the application area is in a GSM network, then the CO could be Mobile Switching Centre and the RS the base station (BS). For wireless Local Area Networks (WLANs), the CO would be the headend while the Radio Access Point (RAP) would act as the RS. In narrowband communication systems and WLANs, RF signal processing functions such as frequency up- conversion, carrier modulation, and multiplexing, are performed at the BS or the RAP, and immediately fed into the antenna. RoF makes it possible to centralize the RF signal processing functions in one shared location (headend), and then use optical fiber, which offers low signal loss (0.2 dB/km for 1550 nm, and 0.5 dB/km for 1310 nm wavelengths) to provide the signal to the RAUs (figure 1.3).

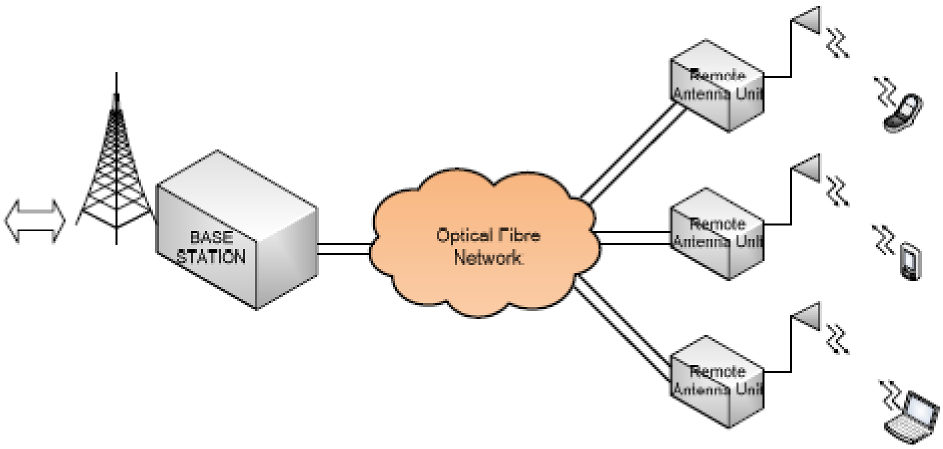


Figure 1.3- Radio over Fiber system [Francisca Martínez, 2007]

RAUs only need to perform optoelectronic conversion and amplification functions simplifying being significantly simplified. Equipment sharing, dynamic allocation of resources, and simplified system operation and maintenance are assured with the centralization of RF processing functions, these benefits can translate into major system installation savings, especially in wide-coverage broadband wireless communication systems, where a high density of BS/RAPs is necessary [Francisca Martínez, 2007].

A wide range of benefits associated with using this technology supports the popularity and proliferation of technology-based ROF systems. This section aims to describe in detail the main advantages associated with using ROF over other transmission techniques.

Low Attenuation

In free space, losses due to absorption and reflection increase with frequency, reason why electrical distribution of high-frequency microwave signals in free space or through transmission lines is problematic and costly. In transmission lines, impedance rise with frequency as well, leading to very high losses, therefore distributing over long distances high frequency radio signals electrically requires expensive regenerating equipment. The distribution via the use of transmission lines of mm-waves is not feasible even for short distances, the solution to this problem is to distribute baseband signals or signals at low intermediate frequencies (IF), which need to be up-converted to the required microwave frequency, amplified and then radiated at each base station. The solution described above places stringent requirements (such as linearity) on repeater amplifiers and equalizers, high performance local oscillators will be needed in addition, for up conversion at each base station. Such arrangement leads to complex base stations with tight performance requirements. The alternative solution is to use optical fiber witch has lower losses. With RoF technology it is possible to have simplification of remote antenna units, which is a substantial improvement, in addition low-loss distribution of mm-waves can be achieved. Nowadays commercially available fibers have much lower losses than other devices used for the same purpose, for example coaxial cables have losses about three orders of magnitude higher at higher frequencies than optical fiber, Single Mode Fibers (SMFs) made from silica have attenuation losses below 0.2 dB/km and 0.5 dB/km in the 1550 nm and the 1300 nm windows (figure 1.4).

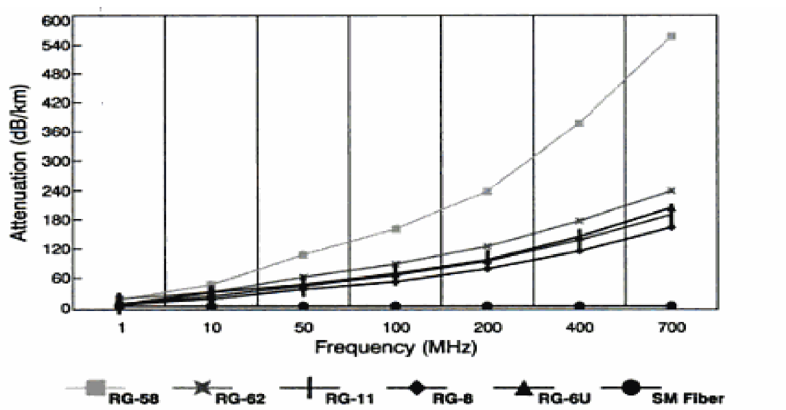


Figure 1.4 - Comparison of cooper coax versus optical fiber cable [Goff, 2002]

Observing the graph above, RG-58 has an attenuation rate of 100 db/km at 40 MHZ only 0.00000001 % of the signal strength would remain after 1km of cable, by comparison the single mode fiber optic cable has an essentially flat 0.5 db/km attenuation even at 500 MHZ [Goff, 2002].

Therefore, by transmitting microwaves in the optical form, transmission distances are increased severally and the required transmission powers reduced greatly.

Large bandwidth

The bandwidth offered by optical fibers is enormous when compared with other technologies. For single SMF optical fiber 50 THz of bandwidth are possible to achieve corresponding to the three main transmission windows, namely the 850 nm, 1310nm and 1550nm wavelengths. In practical terms, only about 1.6 THz of the total bandwidth capacity are used by commercial systems, however researches to exploit more optical capacity per single fiber are still continuing [Thyagarajan, 2003]. Apart from the high capacity for transmitting microwave signals the bandwidth of optical fibers offer, other benefits must be taken into account.

The high optical fiber bandwidth enables high speed signal processing that is very difficult or impossible to do with electronic systems, some microwave functions such as mixing, filtering, up and down conversion are easily implemented in optical terms. As example, mm-wave filtering is achieved by first converting the electrical signal to be filtered into an optical signal, then filtering by using optical components such as Mach-Zehnder interferometer or fiber Bragg gratings (FBG) and finally converting the signal back into electrical form. The utilization of the enormous bandwidth of optical fibers is hampered by the limitation in bandwidth of electronic systems, which are the most used sources and receivers of transmission data. In RoF technology, Sub-Carrier multiplexing (SCM) is used to increase optical fiber bandwidth utilization. In SCM several microwave subcarriers, which are modulated with digital or analogue data, are combined and used to modulate the optical signal, which is then carried on a single fiber, this make RoF systems very cost-effective.

Immunity to Radio Frequency Interference

Immunity to Electromagnetic interference (EMI) is a massive benefits of using optical fiber in communication systems, especially using microwave signals, even for short connections at mm-waves fiber cables are preferred. Related to EMI immunity is the immunity to eavesdropping, which is an important characteristic of optical fiber communications, as it provides privacy and security

Easy Installation and Maintenance

Most used RoF techniques get rid of the need for a Local oscillator and related equipment at the RAU, in such case a photo detector, an RF amplifier and an antenna make up the RAU. RoF systems are implemented so that complex and expensive equipment is kept at the headend, making the RAUs much simpler. Complex equipment is located in the headend of the system and shared by several RAUs, such an arrangement leads to lighter and considerably smaller RAUs, drastically reducing installation and maintenance costs. Low maintenance costs and easy installation of RAUs are, because of the large number of RAUs required, a very important requisite for mm-waves systems. In addition, in most systems RAUs are not easily accessible, the reduction in maintenance requirements leads to major operational cost savings.

We can also imagine that in an environment with a considerable number of RAUs oversized interfaces would lead to visual pollution, so the idea of smaller RAUs also leads to environmental impact.

Reduced Power Consumption

Smaller and simpler RAUs reflect in reduced power consumption. Some applications, such as Fiber radio systems operating at 5 GHz, employing picocells can have RAUs operate in passive mode. Reduced power consumption at the RAU is a significant bonus to the system, because sometimes RAUs are placed in remote locations fed in the form of light through the fiber, instead of the power grid. Another benefit of Low RF power RAUs is that introduced interferences are substantially lower and network planning is facilitated by the improvement in spectrum efficiency.

Multi-Operator and Multi-Service Operation

RoF technology offers operational flexibility. Its possible to make RoF distribution system signal-format transparent, a good example is the intensity modulation and direct detection (IM-DD) technique, which can be implemented to operate as a linear system or as a transparent system. A transparent system can be achieved using low dispersion fiber (SMF) and pre-modulated RF subcarriers (SCM). Using the technique described RoF networks can distribute multi-service traffic and multi-operator resulting in enormous economic savings and a dynamic system. Optical Frequency Multiplication (OFM) techniques have the attribute of being tolerant to chromatic dispersion, combining it with either WDM or SCM can be used to complete multi-service operation.

Dynamic Resource Allocation

In ROF systems capacity can be allocated dynamically thanks to most of the RF functions (such as modulation, switching) being performed at a centralized headend. This can be achieved by allocating optical wavelengths through Wavelength Division Multiplexing (WDM) as need arise. An example is RoF distribution system for GSM traffic, more capacity can be allocated to an area (e.g. stadium at a football game or a shopping centre) during peak times and then re-allocated to other areas when off-peak (e.g. to populated residential areas in the evenings), a practical case is the Sydney Olympics ROF system implemented by the company BriteCellTM which will be briefly described later in. It is obvious that in situations as the ones described before allocating permanent capacity would be a huge waste of resources in cases where traffic loads vary frequently and by large margins, we can take as example the situation of a football game in some stadium where at match days massive wireless traffic is achieved, but otherwise almost no communications are made. Additionally centralized headends make easier the consolidation of signal processing functions such as mobility functions and macro diversity transmission.

Other benefits are also:

- Line-of-sight (LOS) operation, minimizing the multipath effects;
- Reduction in the number of handovers;
- Support for future broadband multimedia applications;

In terms of completing this section, as set out above distributed antenna systems like the ones used by RoF technology provide a solid infrastructure with the potential for adaptative antenna selection and adaptative channel allocation to increase spectrum efficiency. A case study of a successful implementation of a ROF system is the BriteCellTM ROF system used at the 2000 Sydney Olympics. The BriteCellTM fiber optic-based mobile communication system designed by Tekmar Sistemi was installed for the Sydney 2000 Olympics in order to handle the massive wireless traffic (especially at the opening and closing ceremonies).

On the opening day of the Olympics, over 500,000 wireless calls were made from Olympic Park venues. In the minutes leading up to the opening ceremony, over 175,000 calls were made by the 110,000 spectators in the sold out stadium.

Some vital features of the ROF system installation were:

1. Support for dynamic allocation of network capacity.
2. Support for 3 GSM operators.
3. Support for both 900 MHz and 1800 MHz cellular networks.
4. More than 500 remote antenna units (RAUs) were deployed.
5. Multiple layers of wireless in building and external Picocell coverage systems were installed.
6. System was able to support the equivalent of 75% of Sydney's average central business district traffic.

Distributed antenna systems provide an infrastructure with the potential for adaptive antenna selection and adaptive channel allocation to increase the spectrum efficiency

1.3 Objectives and structure

The objectives of this work are:

- Study of the basic concepts associated with ROF, and the analysis of the effects introduced in propagated ROF links by the main constituent components of a PON;
- Presentations of a frequency multiplication technique using the MZM in a non-linear regime, and validation using simulation software;
- Obtaining a passive optical network with multi-channel OFDM signals, compatible with UWB, generated by frequency multiplication in the optical domain;

This document is divided in six chapters, which present and discuss several topics about Radio over Fiber systems.

The first chapter presents the context of RoF technologies, and some important concepts associated the main motivations for the use of such systems and some advantages of incorporating RoF signals distribution in actual networks. The main objectives of this work are also presented.

Chapter 2 describes the main components of a RoF link, and the properties and main limitations associated, as well as ways to overcome them.

In the third chapter we present several experimental studies on the impact of optical impairments in RoF systems, as well as the practical testing of theoretical concepts explained in chapter 2.

The fourth chapter presents several simulations to test and validate the possibility of obtaining optical frequency multiplication, with low cost components, in transparent networks, of low complexity, using amplitude modulation and OFDM modulation formats with DSB and DSB- CS modulators. Several setups were used allowing UWB generation and distribution with multi-carrier modulation. A comparative study of the benefits of using DSB or DSB-CS modulators for this kind of optical systems is made.

Chapter five aggregates the systems studied in chapter four in a novel network, using WDM concepts. It consists of a RoF-WDM network, which allows multi/unicast distribution of OFDM signals, UWB compatible, generated recurring to optical frequency multiplication.

Finally in chapter 6, the final conclusions of the performed work are presented, and some future research directions are proposed.

1.4 Main contributions

The main contributions of this work are:

- Presentation of the basic concepts associated with the use of ROF technology, in concrete an extensive analysis of the impact of the optical components in the performance of RoF signals;
- Experimental demonstration of optical impairments that occur in RoF links and decrease system performance, in back to back transmission and with SSMF, to help understand how to overcome this limitations and identify which components are responsible;
- Understanding how the use of MZM in a non linear regime can enable obtaining optical frequency multiplication and how it can contribute to reduce system costs, and thus achieve cost-efficient solutions;
- Simulation work in order to verify the possibility of obtaining optical frequency multiplication using DSB and DSB-CS modulation, with simple modulation formats such as amplitude modulation, and advanced modulation format OFDM to increase spectrum efficiency;
- Validating the studied concepts through the implementation of a final scenario consisting of a passive optical network with multi-channel OFDM signals, compatible with UWB, generated by frequency multiplication in the optical domain

Besides of this contribution some documents were submitted for the proceedings of conferences:

- Gabriel Gonçalves, António Teixeira, Mário Lima, “Optical Generation and Distribution of OFDM Ultrawideband Signals Over Fiber”, AccessNets, Budapest, Hungary, 2010;

- Gabriel Gonçalves, António Teixeira, Mário Lima, “OFDM-UWB optical generation and distribution over PON”, SEON- Symposium on enabling Optical Networks and Sensors, 2010.

Chapter 2. Optical and electrical components of a RoF system and associated impairments.

2.1. Introduction

Radio signals distributions have some limitations, which are overcome successfully using optical fiber due to its large bandwidth. To understand how ROF systems work it is important to know limitations associated with each of these elements and how these can be overcome. Besides the importance associated to the main constituent of the PON system, which is the optical fiber itself and the high bandwidth related, other elements must be taken into account. The aim of this section is to present the basic elements constituting a system of radio transmission over fiber as well as describe the main impairments and possible ways to improve/avoid them.

Going through the sequence of elements constituting the ROF system from the transmitter until the receiver:

2.2 Laser

The light source most commonly used in optical communications is the semiconductor laser diode, mainly due to its property to generate high power outputs with a narrow-linewidth radiation, providing a better coupling of the light to the fiber and also because of the higher bandwidth when compared to LED´s. Laser diodes are essentially oscillators with amplification, feedback and frequency selection mechanisms. A semiconductor laser consists of an active medium consisting of atoms, molecules and ions capable of emitting radiation, an external energy pump source whose purpose is to stimulate the atoms in the active medium, and a resonant optical cavity formed by mirrors where the photons are reflected.

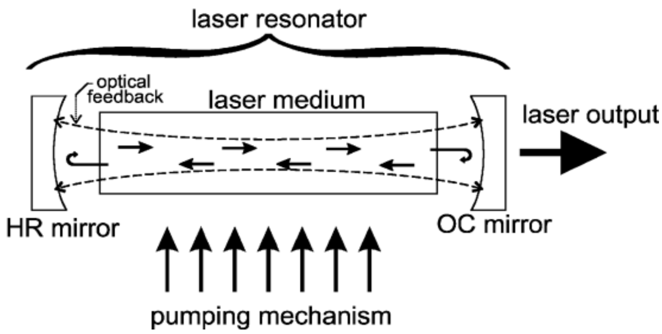


Figure 2.1 - Elements of a typical laser oscillator [Pospiech, 2004]

There are four main types of lasers they are the Fabry-Perot (FP) laser, the distributed feedback (DFB) laser, tuneable lasers and the vertical cavity surface-emitting laser (VCSEL). The FP laser has a lasing cavity defined by two end faces acting like reflecting mirrors. Since the cavity is fairly long, the laser will oscillate simultaneously in several modes or frequencies creating a spectral broad output that does not make the FP laser a good solution for high-speed or long haul transmissions. In a DFB laser, a series of closely spaced reflectors provide the light feedback throughout the cavity making possible that light will only oscillate in a single mode, with very narrow linewidth. For multi-wavelength networks where many lasers are used to transmit in closely spaced wavelengths on the same fiber, the ability of tuning a precisely wavelength for each channel leads to the importance of using tuneable lasers. Finally VCSEL provide an easy and highly efficient way to couple light trough optical fiber, thanks to a stack of up to 30 thin mirroring layers placed on both sides of a semiconductor wafer to form a lasing cavity, however, the manufacture of such lasers is extremely complex.

Three key processes characterize the operation of a laser, photon absorption, spontaneous emission and stimulated emission. When a photon with energy hν enters the laser cavity, an electron state E1 can absorb its energy and excites to the E2 state. If this state is unstable, the electron will return quickly to the origin state emitting a photon with energy hν. When a photon is emitted without external stimulation this phenomenon is called spontaneous emission. The other situation is that stimulated emission occurs only when the electron is stimulated by an external source originating a new photon in phase with the first used to stimulate. As state before, the laser diode is essentially an oscillator with amplification, feedback and frequency selection mechanisms. Figure 2.2 shows a schematic illustration of the main processes of a laser.

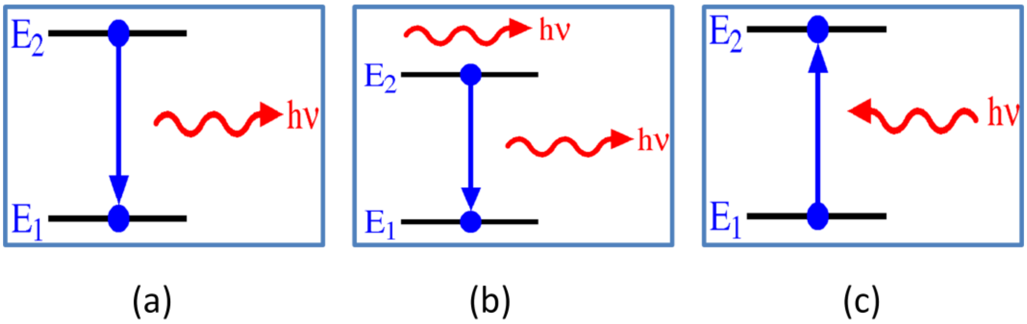


Figure 2.2- a) spontaneous emission, b) stimulated emission, c) absorption

A necessary condition for all photons to be added in phase is that only the frequencies fosc, that verify the following condition can be produced by the cavity, fosc=Lc/2m, where Lc is the cavity length. To each value m, a corresponding longitudinal mode exists, although there are numerous possible modes, only for those, which the cavity's material presents a gain higher than a given threshold will be produced. The higher the number of modes that fulfil this condition, the higher will the laser's spectral width. The situation is described below (figure 2.3).

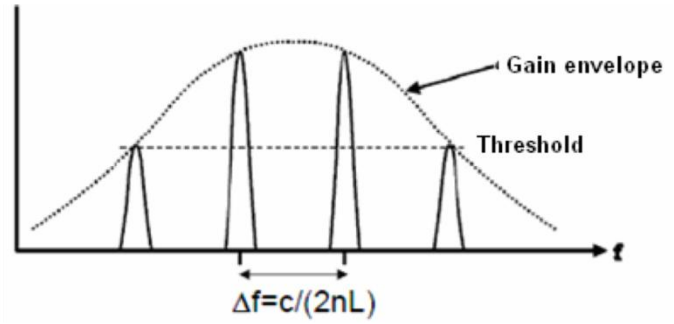


Figure 2.3 - Laser spectral width [Pospiech, 2004]

Another important type of lasers is single-frequency lasers, this type of laser operate on a single resonator mode, so that it emits quasi-monochromatic radiation with a very small linewidth and low phase noise. Very low intensity noise is also achieved using SFL, because any mode distribution noise is eliminated. In laser diodes, there is some small amount of optical power in various resonator modes, even though one mode is clearly dominating. This is because such modes may be only slightly below the laser threshold, so that spontaneous emission can already generate some substantial power. The mode suppression ratio (MSR) is then defined as the power of the lasing mode divided by that in the next strongest mode. Making the laser resonator more frequency-selective can optimize it. Single-frequency lasers can be very sensitive to optical feedback. Even if less than a millionth of the output power is sent back to the laser, this may in some cases cause strongly increased phase noise and intensity noise or even chaotic multimode operation.

2.2.1 Laser RIN

Intensity noise is an optical power fluctuation of a laser, commonly specified as the relative intensity noise (RIN), which is the power noise normalized to the average power level. The optical power of the laser can be considered to be,

$$P(t) = \bar{P} + \delta \mathrm{P(t)} \quad (2.1)$$

with an average value and a fluctuating quantity δP with zero mean value. The relative intensity noise is then that of δP divided by the average power; in the following, this quantity is called I. The relative intensity noise can then be statistically described with a power spectral density (PSD):

$$S_l(f) = \frac{2}{\bar{P}^2}\int_{-\infty}^{+\infty}(\langle \delta P(t)\delta P(t+\tau)\rangle \exp(i2\pi f\tau)\, d\tau \quad (2.2)$$

which depends on the noise frequency f. It can be calculated as the Fourier transform of the autocorrelation function of the normalized power fluctuations (see the equation), or measured e.g. with a photodiode and an electronic spectrum analyzer. (The factor of 2 in the formula above leads to a one-sided PSD as usually used in the engineering disciplines.) The units of this RIN PSD are Hz^{-1}, but it is common to specify 10 times the logarithm (to base 10) of that quantity in dBc/Hz. The PSD may also be integrated over an interval [f1, f2] of noise frequencies to obtain a root mean square (r.m.s.) value of relative intensity noise,

$$\left.\frac{\delta P}{\bar{P}}\right]_{rms} = \sqrt{\int_{f1}^{f2} S_l(f)df} \quad (2.3)$$

which is then often specified in percent.

2.2.2 Laser Linewidth and phase-noise

The linewidth of a laser, typically a single frequency laser, is the width of its optical spectrum, more precisely, it is the width of the power spectral density of the emitted electric field in terms of frequency, wavenumber or wavelength.

A finite linewidth arises from phase noise if the phase undergoes unbounded drifts, as is the case for free-running oscillators. Drifts of the resonator length can further contribute to the linewidth and can make it dependent on the measurement time. This shows that the linewidth alone, or even the linewidth complemented with a spectral shape (line shape), does by far not provide full information on the spectral purity of laser light. In coherent optical fiber communications Lasers with very narrow linewidth (high degree of monochromaticity) are required.

The linewidth of a laser depends strongly on the type of laser. Optimizing the laser design and suppressing external noise influences as far as possible may further minimize it. Determination of whether quantum noise or classical noise is dominating is essential because the required measures can depend very much on this. The influence of quantum noise (essentially spontaneous emission noise) is small for a laser with high intracavity power, low resonator losses, and a long resonator round-trip time. Classical noise may be introduced via mechanical fluctuations, which can often be kept weaker for a compact short laser resonator, but note that resonator length fluctuations of a certain magnitude have a stronger effect in a shorter resonator. Proper mechanical construction can minimize the coupling of the laser resonator to external vibrations and also minimize effects of thermal drift. There can also be thermal fluctuations in the gain medium, introduced by a fluctuating pump power [Viščor Ivo, 2001].

Single-frequency and fiber lasers can achieve linewidths of a few kilohertz, or sometimes even below 1 kHz. With serious efforts at active stabilization, sub-hertz linewidths are sometimes achieved. The linewidth of a laser diode is typically in the megahertz region, but it can also be reduced to a few kilohertz, e.g. in external-cavity diode lasers, particularly with optical feedback from a high-finesse reference cavity.

Laser phase noise must also be considered in optical links. Due to the dispersive nature of optical fiber, phase modulation (PM) is converted to intensity modulation (IM) during transmission. This process often described as PM-IM conversion, has a noise contribution called dispersive intensity noise and reduces the signal-to-noise ratio at the receiver. Traditionally, the phase noise level has been extracted by measuring the spectral linewidth of the laser. Linewidth is typically measured using the delayed self-homodyne or heterodyne methods with and electrical spectrum analyzer (ESA). This technique only works if inherent laser processes cause the noise spectrum.

The phase noise is frequency dependent, spectral linewidth measurements can be affected by 1/f phase noise at low frequencies [Viščor Ivo, 2001].

2.3 Modulators

2.3.1 Direct modulation of laser diodes

An important parameter when it comes to conveying information through a beam of light, is the modulation, essentially two modulation techniques can be used direct and external modulation, direct modulation, which is the result of directly varying the laser drive current to vary the output optical power of the laser, or the use of external modulation to vary the steady optical power level emitted by the laser. There are implicit limitations to the use of direct modulation including limitations on transmission rates related to the spontaneous and stimulated carrier lifetime and the photon lifetime.

2.3.1.1 Chirp

As seen previously, a very important parameter to be considered when using laser as optical source is the linewidth, directly related with linewidth is another parameter called chirp, when considering transmission on a WDM system the laser linewith will depend on the chirp. Chirp is an undesired frequency variation of the laser's output trough time, which leads to an increase on the bandwidth of each signal, as consequence of the laser's bias current variation associated with direct modulation.

In simulations, chirp is considered to introduce a phase rotation Φ on the optical signal given by:

$$\frac{d\phi(t)}{dt} = \frac{\alpha_H}{2}\,\Gamma\, g_0[N(t) - N_t] \quad (2.4)$$

The chirp of an optical pulse is usually understood as the time dependence of its instantaneous frequency. Specifically, an up-chirp (down-chirp) means that the instantaneous frequency raises (decreases) with time. In semiconductor lasers, chirps can also result from refractive index changes associated with changes in the carrier density. The chirp of a pulse can be removed or reversed by propagating it through optical components with suitable chromatic dispersion.

The combination of chirp and chromatic dispersion, can lead to the pulses broadening creating ISI reducing system performance. For directly modulated lasers, chirp is a major problem, a possible solution to reduce chirp is by controlling the biasing current of the laser or using external Bragg grating. In WDM systems to avoid channels overlapping, the solution is to choose frequencies more spaced among them.

2.3.1.2 AM/FM modulation efficiency

The AM efficiency has to do with the relationship between the amplitude of the output signal we get in terms of input signal, and examining the characteristic curves of polarization presented in the following figures (Figure 2.4, 2.5) the more slope, the greater amplitude curvature we obtain for the output signal depending on the input signal, better distance between maximum and minimum amplitude can be achieved (SNR) and therefore lower distortion introduced in the signal.

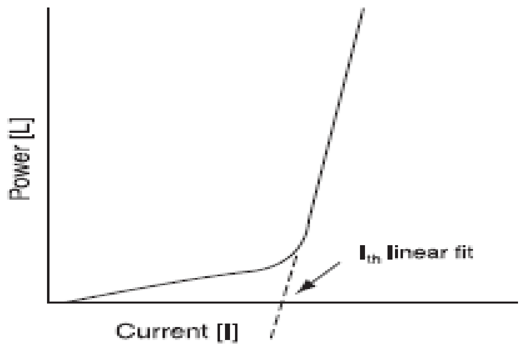


Figure 2.4 – Pout Vs Ibias for direct modulation [Xavier Fernando, 2009]

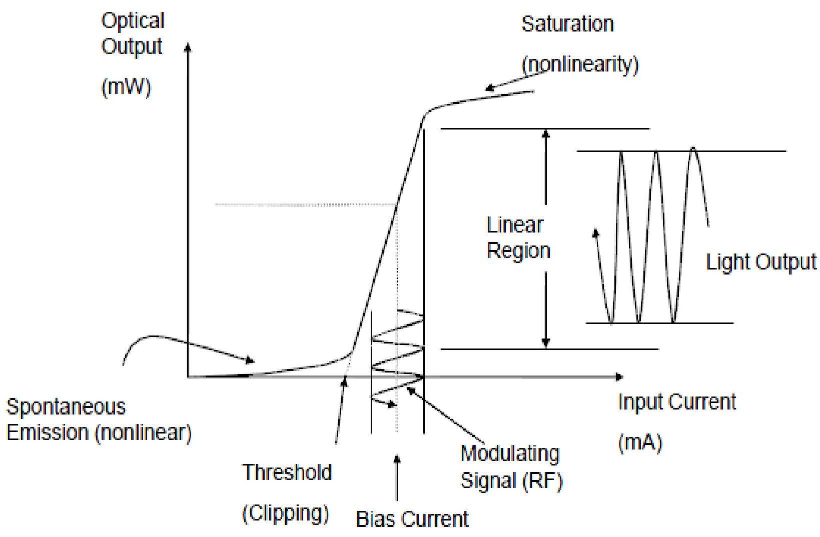


Figure 2.5 – Output light power variation with input current [Xavier Fernando, 2009]

The efficiency with which the laser converts current to usable light is given by the slope of the L-I curve (Figure 2.5), and is called the modulation gain. The wide variation is largely due to differing methods of coupling the light into the optical fiber. The modulation gain also varies somewhat with frequency, so it must be specified whether a particular value is a dc or higher-frequency gain.

Distributed feedback (DFB) semiconductor lasers are promising as light sources for coherent optical communication systems because of their single longitudinal mode operation with narrow spectral linewidth. In such systems, wavelength tunability and a flat frequency modulation (FM) response are also required for the local oscillator and the transmitter, respectively. The carrier-induced FM efficiency of DFB lasers has a large variation with changes in the bias current, and especially, both blue- and red-shifted FM efficiencies are obtained depending on the bias condition.

2.3.1.3 Direct modulation non-linearities: Intermodulation and clipping

As explained before, the laser requires a minimum current to start working and therefore emitting (spontaneous emission), this current is the minimum current threshold (“threshold bias current"). Above this threshold the linear operation area of the laser starts. For very high levels of power input signal, the laser suffers a clipping effect (figure 2.6), which leads to a significant increase of distortion, and consequently considerably deteriorating signal performance.

Clipping occurs when the signal input is too high and some power peaks can occur that extend to the nonlinear area of the laser-biasing curve, which in the output signal is translated into a high level of distortion.

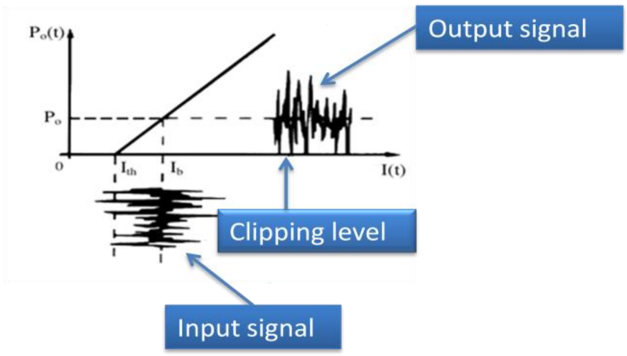


Figure 2.6 – Laser clipping effect.

In the other hand, if the light-current characteristic of laser diodes is fairly linear above threshold, analogue signals may be converted from current to light power. However, since the laser dynamics are intrinsically non-linear, harmonic distortion occur during the conversion process. For low modulation frequencies, harmonic distortions are introduced due to the imperfect linearity of the static light power versus current characteristics. Increasing modulation frequency, harmonic distortions rapidly increase because of the relaxation resonance phenomena, yielding maximum distortions for modulation frequencies of the order of the relaxation resonance frequency.

In fact the imperfect linearity of light versus current characteristics is responsible for nonlinear distortions if the laser diode is still in a quasi-steady-state. This applies for low modulation frequencies (hundreds of Megahertz). In practice if the analogue transmission channel of a laser diode is restricted to from ω_{min} to ω_{max}, if two modulation frequencies within this channel are considered ω_1, ω_2 for example, the second order distortions yield distortion products at 2 ω_1, 2 ω_2, ω_1+ ω_2 and ω_2- ω_1, whereas the third order distortion yield distortion products at 3 ω_1, 3 ω_2, 2 ω_1+ ω_2, 2 ω_2+ ω_1. For high frequencies the intermodulation distortions are no longer only related to the static light –output versus current characteristics, but also to relaxation resonance phenomena [A. Bhardwaj, 2010]. Direct modulation bandwidth of a semiconductor laser is limited by the relaxation oscillations arising from the coupled rate equations that describe the dynamics of the carrier and photon densities inside the laser cavity [A. Bhardwaj, 2010].

2.3.2 External modulation using Mach-Zehnder modulator

When data rates were in the low gigabit range and transmission distances were less than 100 km or so, most fiber optic transmitters used directly modulated lasers. However, as data rates and span lengths grew, waveguide chirp, limited data rates. Dispersion problems resulted when the wavelength chirp widened the effective spectral width of the laser. One solution to the problem is a laser with no wavelength chirp and a narrow linewidth, this solution took the form of external modulation, which allows the laser to be turned on continuously, and the modulation is accomplished outside of the laser cavity. External modulators may be used to transmit digital data stream, or analogue signals, in ROF case.

2.3.2.1 Linear regime

The MZM imposes a nonlinear attenuation to the electrical driving signal,

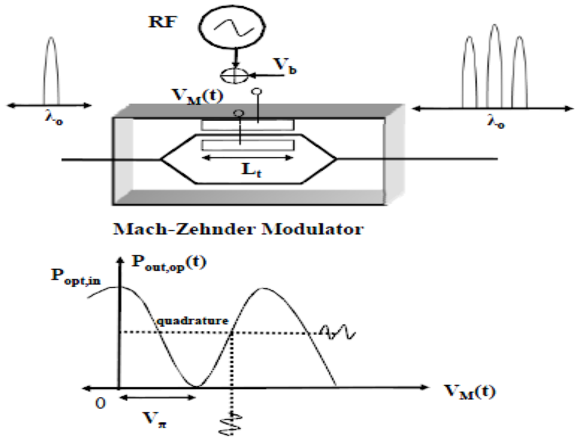


Figure 2.7 - MZM output Vs applied bias voltage [Xavier Fernando, 2009]

The Mach-Zehnder interferometric modulator is a basic building block used in designing analog amplitude-modulated optical communication links. Since the output-intensity/input-voltage characteristic of the Mach-Zehnder modulator has a cosine shape, a multi-tone input signal will generate sums and differences of the input frequencies. These intermodulation products will cause deterioration in the signal-to-noise ratio. In order to improve its intermodulation performance, the Mach-Zehnder modulator is usually operated with 50% optical bias (fig. 2.7). Operating the MZM at quadrature eliminates the even-order distortion products and provides the minimum odd-order distortion products as a function of the output signal strength.

2.3.2.2 – Efficiency

An important parameter related to external modulation using MZM is the efficiency, this concept has to do with the sinusoidal waveform that characterizes the MZM output Vs. The applied driving voltage (see figure 2.8), if maximal amplitude is required at the output of the Mach-zehnder, the device needs to be polarized just 50% of the curve of the waveform in order to have a signal at the output with virtually no distortion, if the polarization is upper or below this, level variations of the phase of the signal will occur and distortion is introduced into the signal decreasing efficiency. However as it will be seen later in next topic, polarizing the external modulator in a non-linear region can have lots of benefits for operations like frequency multiplication.

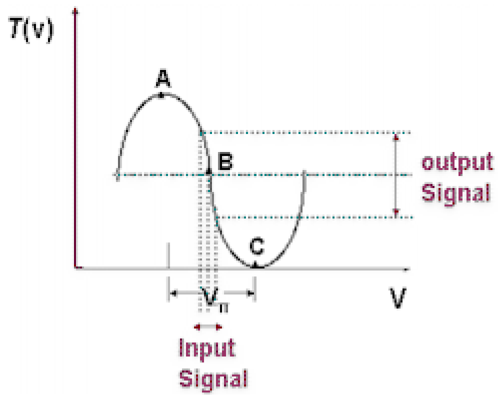


Figure 2.8 – MZM transmission efficiency vs. applied voltage

As it can be seen in figure 2.8, the slope from point A to point C has a direct repercussion in the signal output amplitude in relation to the input signal. The higher slope greater the amplitude of the output signal with respect to the input signal, and hence greater efficiency.

2.3.2.3 – Non linear properties: Frequency multiplication and Intermodulation Products

Associated with the use of the Mach zehnder in a non-linear regime, is a very important concept, which is frequency multiplication. In fact, a selected electrical bias voltage applied to the modulation input causes non-linear modulation of an input optical signal with one or more even integral multiples of an electrical input signal which is additionally applied to the modulation input, thereby providing frequency multiplication. As an example, in order to obtain frequency doubling using a Mach-Zehnder modulator the

MZM need to be dc-biased at the peak output power (Vπ – fig. 2.8), this way the odd order sidebands are suppressed at the output of the MZM (see chapter 4).

A non-linear characteristic associated with the use of external modulators, such as the MZM, is Intermodulation or intermodulation distortion (IMD). This phenomenon consists in the unwanted amplitude modulation of signals containing two or more different frequencies. The intermodulation between each frequency component will form additional signals at frequencies that are not, in general, at harmonic frequencies (integer multiples) of either, but instead often at sum and difference frequencies of the original frequencies.

Intermodulation products are caused by non-linear behavior of the signal processing being used. The theoretical outcome of these non-linearities can be calculated by conducting a Volterra series of the characteristic, while the usual approximation of those non-linearities is obtained by conducting a Taylor series.

Intermodulation essentially creates spurious emissions (sidebands, frequency components at the sum and difference of the input frequencies, and possibly at other frequencies). This can create minor to severe interferences for other operations on the signal. It should not be confused with general harmonic distortion (which does have widespread use).

2.4 Optical fiber

In a communication system optical fiber is a key element to ensure propagation. When impulses propagate along the fiber innumerable effects, both linear and non-linear, affect the system performance. In fact, fiber has innumerous effects, which affect the shape and spectral content of impulses, degrading transmission conditions. Such effects can establish a limitation in transmission distance and transmission rate that is why it is important to study them and try to ameliorate transmission toleration.

Depending on the number of modes allowed optical fibers could be single-mode or multi-mode. Multi-mode fibers have higher number of modes with an increase of the core diameter and numeric aperture, these facts lead to a high intermodal dispersion that reduces the transmission bandwidth, besides of those inconvenients multi-mode fibers provide an easy light coupling.

With regard to limitations imposed by the properties of fiber in the transmission of radio signals, two types of phenomenas can occur linear and non-linear.

2.4.1 Linear properties

Attenuation and chromatic dispersion are the two majors' linear properties of optical fiber. Attenuation of a light signal as it propagates along a fiber is an important factor to take in account when determining the maximum transmission distance between two points, fulfilling certain requisites. Dispersion is the pulse spreading that occurs when propagating along the fiber, making harder the signal's recovery, leading to a signal to noise ratio (SNR) reduction. On the other hand dispersion can be classified as intramodal or chromatic dispersion, and intermodal dispersion depending on the number of modes that are involved, chromatic dispersion on a single mode and intermodal dispersion on multi-mode fibers.

2.4.1.1 Attenuation

Fiber attenuation is a way to quantify the optical signal power losses during the signal transmission. Attenuation suffered by the optical impulses vary according to an exponential law depending of the distance:

$$P(x) = P_0 . e^{-\alpha_p \cdot x} \quad (2.5)$$

Where α_p is the attenuation coefficient of the fiber expressed in km and P_0 is the optical power when starting the propagation, x is the distance travelled. In optical fiber the common procedure is to express attenuation in dB/km,

$$\alpha(dB/km) = \frac{10}{x} \cdot \log\left[\frac{P(0)}{P(x)}\right] = 4.343 \cdot \alpha_p \ (km^{-1}) \quad (2.6)$$

Several variables, such as propagating wavelength, absorption, scattering and radiation losses must be taken into account regarding attenuation.

Absorption losses can be caused by atomic defects in the glass composition of the fiber, intrinsic absorption by the atoms of the fiber material and extrinsic absorption by impurity atoms in the glass material.

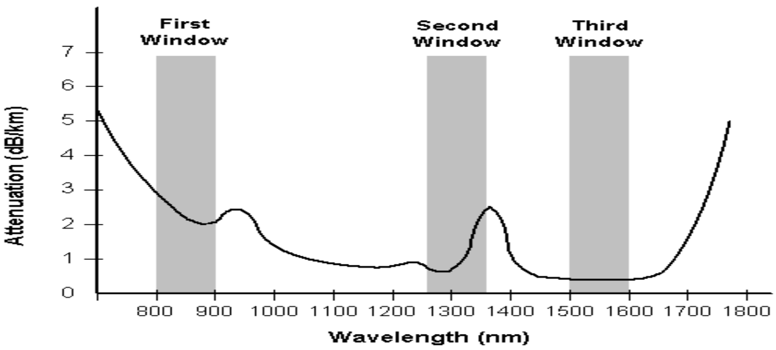


Figure 2.9 - Attenuation for the three main windows of transmission on optical fiber [fiber-optics, 2010]

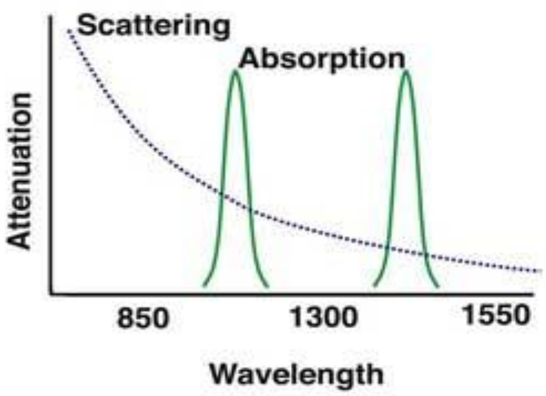


Figure 2.10 - Scattering and absorption for different wavelengths [fiber-optics, 2010]

Microscopic variations in the material density caused by compositional fluctuations and defects occurred during the fiber manufacture result in the scattering losses. Scattering losses can be divided in three types: Rayleigh, Brillouin and Raman scattering.

Rayleigh scattering is due to fluctuations of the silica's density, which result into refractive index variations. Radiation losses occur when the propagation wave goes through a bend of finite radius or curvature. The existence of irregularities on the core-cladding interface and micro bending is also the cause of this type of losses. Attenuation can be problematic in long-haul transmission links, introducing considerable power losses, despite the fact that in the third window attenuation per km was significantly reduced.

2.4.1.2 Chromatic Dispersion and induced RF power fading

Chromatic dispersion is the pulse spreading that occurs within a single mode, it is a result of the group velocity being a function of the wavelength, that result in different spectral components travel at different speeds inside the fiber. Due to its dependence on group velocity chromatic dispersion is also known as group velocity dispersion (GVD). Two main components affect chromatic dispersion, material dispersion and waveguide dispersion. Material dispersion occurs because silica's refractive index changes with frequency, causing a wavelength dependence of the group velocity for any given mode. Waveguide dispersion has to do with how the energy distribution between the fiber core and cladding. Only 80 % of the optical power is confined to the core, the 20% of the light that propagates through the cladding travels faster than the light confined to the core, which makes intramodal dispersion dependent on the optical fiber dimensions.

The simplest technique for the optical generation and distribution of the RF signal modulated with data is an intensity modulation scheme via direct or external modulation of a laser. Since direct modulation suffers from the effects of laser frequency chirp externally modulated optical fiber links are the preferred choice. In conventional intensity modulation, the optical carrier is modulated to generate an optical field with the carrier and two sidebands (double-sideband (DSB) modulation). At the optical receiver, each sideband beats with the optical carrier, thereby generating two beat signals which constructively interfere to produce a single component at the RF frequency. However, if the signal is transmitted over fiber, chromatic dispersion causes each spectral component to experience different phase shifts depending on the fiber-link distance, modulation frequency, and the fiber-dispersion parameter. These phase shifts result in relative phase differences between the carrier and each sideband, and produce a phase difference in the two beat signals at the RF frequency, which results in a power degradation of the composite RF signal [J. Ma, 2007].When the phase difference is π, complete cancellation of the RF signal occurs. As the RF frequency increases, the effect of dispersion is even more pronounced and the fiber-link distance severely limited. Additionally in RoF systems, the fiber chromatic dispersion can degrade the transmitted Radio Frequency (RF) signal by means of fading effects [J. Ma, 2007][A. Hilt, 2002]. The fading effect can lead to cosine like fluctuation of the signal power along the fiber, which means that the signals periodically vanishes at specific pairs of frequencies and fiber lengths. This phenomenon happens because sidebands around the optical carrier, arising from modulation process, travel into the optical fiber with different group velocities, since they experience different values of chromatic dispersion.

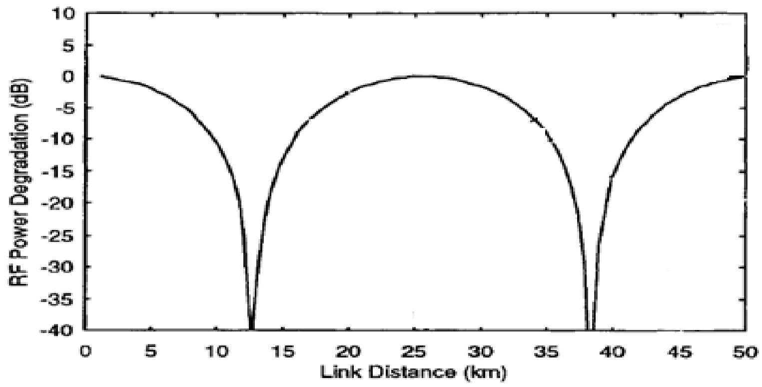


Figure 2.11- RF power fading effect with fiber distance [Gliese, 1997]

We can define RF power degradation as the difference in the post-detection RF powers before and after transmission through the optical fiber. Fig. 1 shows the predicted RF power degradation due to dispersion as a function of fiber length for various values. As observed in figure 2.11 [Gliese, 1997], for this ROF system used as example, the RF power is totally cancelled for values around 12, and 37 km of optical fiber.

2.4.2 Non - Linear properties

2.4.2.1 Stimulated Raman Scattering

Stimulated Raman Scattering (SRS) is much less of a problem than SBS. Its threshold is close to 1 Watt, nearly a thousand times higher than SBS. But real systems are being deployed with EDFAs having optical output powers of 500 mW (+27 dBm), and this will only go higher. A fiber optic link that includes three such optical amplifiers will reach this limit since the limit drops proportionally by the number of optical amplifiers in series. SRS can cause scattering like SBS, but usually the effect first seen is that the shorter wavelength channels are robbed of power, and that power feeds the longer wavelength channels. This is similar to the operation of EDFAs where a 980 nm pump wavelength provides the energy that amplifies the signals in the longer wavelength, 1550 nm region.

2.4.2.2 Stimulated Brillouin Scattering

Stimulated Brillouin Scattering (SBS) sets an upper limit on the amount of optical power that can be usefully launched into an optical fiber. When the SBS threshold for optical power is exceeded, a significant amount of the transmitted light is redirected back to the transmitters. In addition to causing a saturation of optical power in the receiver, problems also arise with back reflections in the optical signal, and noise that degrades the BER (Bit error rate) performance. Brillouin scattering is the time-varying electric fields within a fiber interacting with the acoustic vibrational modes of the fiber material, which in turn scatter the incident light. Stimulated Brillouin Scattering is when the source of the high intensity electric fields is the incident lighwave. The periodic variation in the refractive index, caused by the high power incident lightwave, cases back reflection similar to the effect of Bragg gratings. An increasing portion of light is backscattered because of the increasing optical level beyond the SBS threshold. This creates an upper limit to the power levels that can be carried over the fiber. Figure 2.13 illustrates this phenomenon. As the launch power is increased above the threshold, there is a dramatic increase in the amount of backscattered light. Wavelength (the threshold is lower at 1550 nm than 1310 nm) and the linewidth of the transmitter, among other parameters, govern the precise threshold for the onset of the SBS effect. Values of +8 to +10 dBm are typical for direct modulated optical sources operating at 1550 nm over standard single-mode fiber.

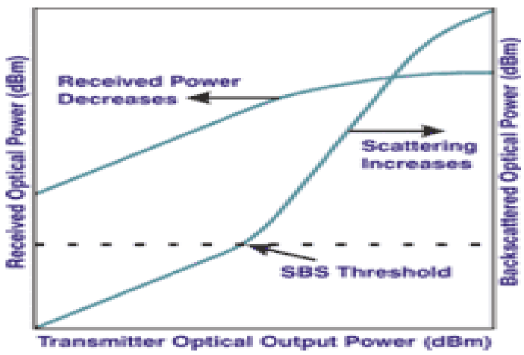


Figure 2.12 - SBS Threshold Effects [fiber-optics, 2010]

The SBS threshold is strongly dependent on the linewidth of the optical source, narrow linewidth sources having considerably lower SBS thresholds. Extremely narrow linewidth lasers (e.g. less than 10 MHz wide), often used in conjunction with external modulators, can have SBS thresholds of +4 to +6 dBm at 1550 nm. Broadening the effective spectral width of the optical source minimizes SBS. Externally modulating the transmitter provides one way to broadening the linewidth. This involves adding a small AC modulation signal to the DC current source used to drive to laser. This broadens the spectral linewidth of the transmitter and increases the threshold for the onset of SBS. This option also increases the dispersion susceptibility of the transmitter, primarily a concern when operating at 1550 nm over non dispersion-shifted single-mode fiber. Practical implementations of SBS suppression circuitry based on laser drive dithering can increase the SBS threshold by 5 dB.

2.4.2.3 Self-phase Modulation

Self-phase modulation (SPM) is due to the power dependency of the refractive index of the fiber core. It interacts with the chromatic dispersion in the fiber to change the rate at which the pulse broadens as it travels down the fiber. Whereas increasing the fiber dispersion will reduce the impact of FWM, it will increase the impact of SPM. As an optical pulse travels down the fiber, the leading edge of the pulse causes the refractive index of the fiber to rise, resulting in a blue shift. The falling edge of the pulse decreases the refractive index of the fiber causing a red shift. These red and blue shifts introduce a frequency chirp on each edge, which interacts with the fiber's dispersion to broaden the pulse.

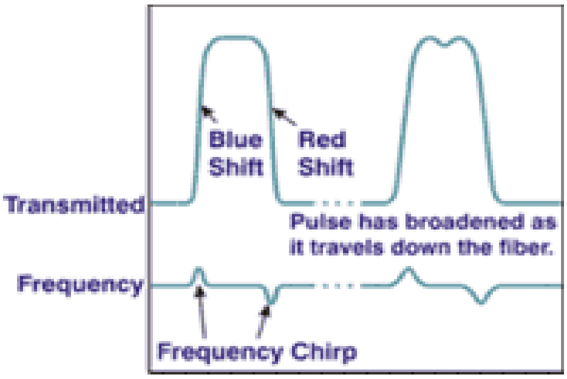


Figure 2.13 - Self-Phase modulation [fiber-optics, 2010]

2.4.2.4 Cross-phase Modulation

Cross-phase modulation (XPM) is very similar to SPM except that it involves two pulses of light, whereas SPM needs only one pulse. In XPM, two pulses travel down the fiber, each changing the refractive index as the optical power varies. If these two pulses happen to overlap, they will introduce distortion into the other pulses through XPM. Unlike, SPM, fiber dispersion has little impact on XPM. Increasing the fiber effective area will reduce XPM and all other fiber nonlinearities.

2.4.2.5 Four Wave Mixing

FWM is a characteristic limitation introduced in DWDM systems. Essentially FWM is caused by the nonlinear nature of the refractive index of the optical fiber itself, and is classified as a third-order distortion phenomenon. Third-order distortion mechanisms generate third-order harmonics in systems with one channel. In multichannel systems, third order mechanisms generate third-order harmonics and a gamut of cross products, these cross products cause several problems since they often fall near or on top of the desired signals. For example considering a three-wavelength system (lets say I1, I2 and I3), that is experiencing FWM distortion, in this simple system, nine cross products are generated near I1, I2 and I3 that involve two or more times of the original wavelengths. Assuming that the input wavelengths are I1=1551.72 nm, I2=1552.52 nm and I3=1553.32 nm. The interfering wavelengths of most concern in the hypothetical scenario are: I1+I2-I3= 1550.92 nm, I1-I2+I3= 1552.52 nm, I2+ I3I1= 1554.12 nm, I1-I2+ I3=1552.52 nm, 2I1-I3= 1550.12 nm, 2I3- I1= 1554.92 nm, I2+ I3-I1= 1554.12 nm, 2I2- I1= 1553.32 nm, 2I3 -I2= 1554.12 nm. It can be seen that three of the interfering products fall right on top of the original three signals. The remaining six products fall outside of the original three signals, these six can be optically filtered out. Because the three interfering products that fall on top of the original signals are mixed together, they cannot be removed by any means. The results can be seen graphically on Figure 2.14. The three tall solid bars are the three original signals, the short cross - hatched bars represent the nine interfering products. The number of interfering products increases as $\frac{1}{2} \times (N^3 - N^2)$(2.7) where N is the number of signals involved in the system.

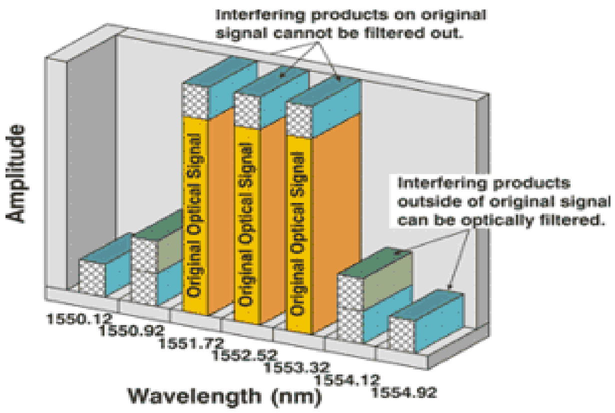


Figure 2.14 - FWM products for a three-wavelength system [fiber-optics, 2010]

Figure 2.15 shows that the number of interfering products rapidly becomes a very large number. Since there is no way to eliminate products that fall on top of the original signals, the only hope is to prevent them from forming in the first place.

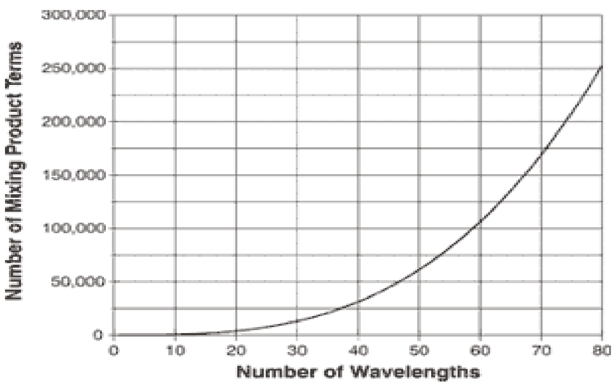


Figure 2.15 - FWM products versus channel count [fiber-optics, 2010]

Two main factors have a strong influence in the magnitude of the FWM products, both referred as the FWM mixing efficiency. The first factor is the channel spacing, mixing efficiency increases dramatically as the channel spacing becomes closer. The second factor was already explained previously and is fiber dispersion, mixing efficiency is inversely proportional to the fiber dispersion, being strongest at zero-dispersion point. As a note, FWM mixing efficiency is expressed in dB and more negative values are better since they indicate a lower mixing efficiency.

Figure 2.16 shows the magnitude of FWM mixing efficiency vs. fiber dispersion and channel spacing.

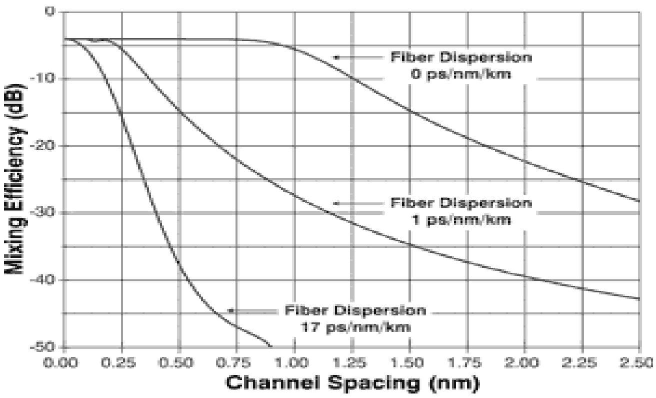


Figure 2.16 -FWM mixing efficiency vs fiber dispersion and channel spacing

If a system design uses NDSF with dispersion of 17 ps/nm.km and the minimum recommended Telecommunication Union (ITU) DWDM spacing of 0.8 nm, then the mixing efficiency is about -48 dB and will have little impact. On the other hand, if a system design uses DSF with a dispersion of 1 ps/nm/km and a non-standard spacing of 0.4 nm, then the mixing efficiency becomes -12 dB and will have a severe impact on system performance, perhaps making recovery of the transmitted signal impossible.

2.5 Semiconductor Optical Amplifier

The applications of SOA in optical communications networks can be divided into three principal functions: booster amplifier to increase transmitter laser power, in-line amplifier to compensate losses due to the transmission through fiber links and preamplifier to improve the receiver sensitivity. These applications are illustrated in Figure 2.17.

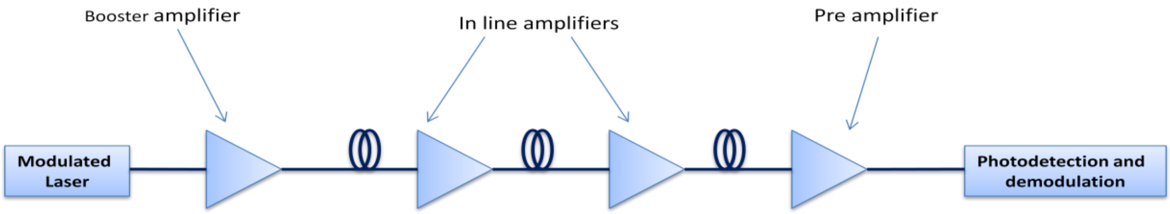


Figure 2.17 - SOA main functions on optical networks.

Optical amplifiers have a very important role in the growth of optical communication networks. Initially these elements where mainly used to compensate fiber losses, however they fast evolved to complete other requirements of optical communication networks. Activities such as optical switching, wavelength conversion, amplifying modulated light signals are nowadays possible due to advances of semiconductor optical amplifiers (SOA) technologies.

SOA consists in a device driven by an electrical current that amplifies the optical signal via stimulated emission in the active region. Implicit with amplification is the introduction of noise to the system, this effect is called amplified spontaneous emission (ASE). A serious problem associated with SOA amplifiers is that the amplifier gain dynamics is not a slow process, leading to gain saturation. The input signal of a SOA directly influences his gain, as its power increases the gain will decrease due to amplifier saturation. In SOA amplifiers the reaction to changes in the input signal is relatively quick because the gain is determined by the carrier recombination lifetime (picoseconds). Another problem of this type of amplification is not having a linear behaviour, this fact can create frequency-chirping, generation of intermodulation products, in multi-channel systems interchannel crosstalk. Some of these non-linear properties can be huge problems in the system performance, but in the other hand may be beneficial in operations such as wavelength conversion.

In RoF systems more than one service can be shared over a same trunk of fiber and this will implicate that different signals may be coupled coming from different arms of the optical network. As it was specified before, PON is a good solution for radio signals propagation and the use of a booster amplifier located at the central office is a reliable solution to compensate the losses due to the PON splitting.

2.5.1 Saturation phenomena and Noise figure

As the input power to the SOA is increased, the gain decreases due to depletion in the career density of the active region of the SOA. The saturation power is defined as the optical power at which the gain drops by 3 dB from the small signal value. Saturation power limits the maximum combined power over all the channels that an SOA can handle without showing non-linear effects.

The linear operation regime is defined as the output power out of an SOA where the non-linear effects like cross-gain modulation, cross-phase modulation, four-wave mixing etc. do not affect the input multi-channel signal. The linear regime of the SOA is described in Figure 2.18 and is closely related to the output saturation power. When the average output power is at least 6 dB less than the output saturation power, non-linear effects are not observed and the SOA is in the linear regime. So for an SOA with 13 dBm saturation power, the maximum average output power is 7 dBm (maximum peak power is 10 dBm) for the SOA to be in the linear regime. Further if the gain of the SOA is 15 dB, then the maximum input power that the SOA can handle in the linear regime is -8 dBm.

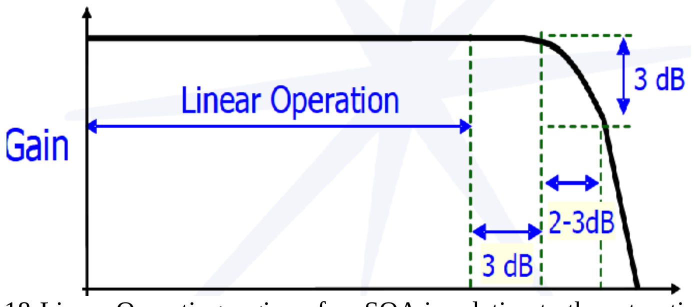


Figure 2.18-Linear Operating region of an SOA in relation to the saturation power

The optical amplification of an SOA is always accompanied by spontaneous emission where photons with random phase and polarization are added to the amplified signal. This result in reduced optical to signal noise ratio (OSNR) at the output of an SOA. The noise characteristics of an SOA are defined by Noise Figure (NF) and are equal to the ratio of the OSNR at the output versus the OSNR at the input. In shot-noise limited detector, the NF of an ideal amplifier is 3 dB. However, due to fiber coupling and waveguide losses, the NF of a packaged SOA is typically between 8-10 dB and is also dependent on the wavelength of the input signal (these effects will be further investigated in chapter 3).

2.5.2 SOA non-linearities

Several SOA nonlinearities can degrade the performance or high-speed optical communication networks, effects such as the carrier density change due to variations in the input signal of the amplifier can cause problems. The main nonlinear effects that occur in the SOA include the following: cross gain modulation (XGM), cross phase modulation (XPM), self gain modulation (SGM), self phase modulation (SPM) and four-wave mixing (FWM, which was explained before). It can be said that the gain and phase of an optical wave propagating through the amplifier are coupled via gain saturation, due to the refractive index of an SOA active region not being constant. In SOA´s carrier density changes in the amplifier have a direct effect in all of the input signals creating SGM, when in the presence of only one channel. Another possibility is that a weak signal at a determinate wavelength can be affected by a strong signal at another wavelength, creating XGM typical of WDM systems, because of the reduce space between each wavelength. SPM can occur as well resulting in phase shifting, when injecting a single channel signal in the SOA, in the other hand if more then one signal is injected into the amplifier it can lead to XPM between signals, but XPM is not always catastrophic to the optical system as it is used to create wavelength converters and other functional devices.

2.6 PIN photodiode

A photodiode allows the conversion of the received optical power into electric current. The PIN photodiode has two regions of semiconductor material, one of type N and other of type P, separated by a lightly doped intrinsic region. Thus, when inversely polarized, the depletion region is increased and the junction's capacity is reduced which enables them to provide higher bandwidth. The presence of the intrinsic region also increases the sensibility to light and provides a region of elevated electric field. The main condition that PIN photodiodes may fulfil is to detect optical signals weither they are strong or very weak, maintaining a good signal-to-noise ratio.

The principal noises associated with photodiodes are the shot or quantum noise, the thermal noise and the noise due to the dark current. Shot noise is a consequence of the random characteristic of the process of photon detection, while thermal noise is originated by the resistive components variation with temperature and the noise due to the dark current occurs even in the absence of light due to current leaks and to the thermal excitation of carriers.

The most important properties of photodiodes are:

The responsivity, which is the photocurrent divided by optical power directly related to the quantum efficiency, dependent on the wavelength, the active area, i.e., the light-sensitive area, the maximum allowed photocurrent (usually limited by saturation), the dark current (in photoconductive mode, important for the detection of low light levels), the speed, i.e. the bandwidth, related to the rise and fall time, often influenced by the capacitance.

The speed (bandwidth) of a photodiode is typically limited either by electrical parameters (capacitance and external resistor) or by internal effects such as the limited speed of the generated carriers. The highest bandwidths of tens of gigahertz are usually achieved with small active areas (diameters well below 1 mm) and small absorption volumes. Such small active areas are still practical particularly for fiber-coupled devices, but they limit the photocurrents achievable to the order of 1 mA or less, corresponding to optical powers of approximately 2 mW or less. Higher photocurrents are actually desirable for suppression of shot noise and thermal noise. Larger active areas (with diameters up to the order of 1 cm) allow for handling of larger beams and for much higher photocurrents, but at the expense of lower speed.

The combination of high bandwidth (tens of gigahertz) and high photocurrents (tens of milliamperes) is achieved in velocity-matched photodetectors, containing several small-area photodetectors, which are weakly coupled to an optical waveguide and deliver their photocurrents into a common RF waveguide structure.

The quantum efficiency of a photodiode is the fraction of the incident (or absorbed) photons, which contribute to the photocurrent. For photodiodes without an avalanche effect, it is directly related to the responsivity S, the photocurrent is, $I = S.P = \frac{\eta e}{h\nu}.P$ with the quantum efficiency η and electron charge e. The quantum efficiency of a photodiode can be very high, in some cases more than 95%, but varies significantly with wavelength. In some cases, additional properties of photodiodes have to be observed, such as linearity of response over a wide dynamic range, the spatial uniformity of response, or the shape of the dynamic response (e.g. optimized for time domain or frequency domain), or the noise performance. The noise performance of photodiodes can be very good. For high photocurrents, it can be limited by shot noise, although thermal noise in the electronics is often stronger than that. For the detection of very low light levels (e.g. for photon counting), the dark current can also play a role. A higher responsivity (although sometimes at the cost of lower quantum efficiency) can be achieved with avalanche photodiodes. These are operated with a relatively high reverse bias voltage so that secondary electrons can be generated (as in photomultipliers). The avalanche process increases the responsivity, so that noise influences of subsequent electronic amplifiers are minimized, whereas quantum noise becomes more important and multiplication noise is also introduced. The electronics used in a photodiode-based photodetector can strongly influence the performance in terms of speed, linearity, and noise.

Due to its quadratic response PIN photodiode can be problematic when receiving RF signals, in fact several beatings are produced introducing distortion the received signal, and replicas of the wanted signal that can superimpose and damage system performance

2.7 Conclusions

The importance of this chapter is to present the various constituent components of a PON, as well as identify and in some cases to find solutions to constraints in the transmission of information, especially in RoF systems. It is extremely important the presentation of these phenomena to better understand the results obtained in the simulations and laboratory work presented in chapters to come. The phenomena associated with the fiber had a special significance in this chapter, since this element is characteristic for providing a high amount of limitations when the spread especially in terms of transmission distance due to attenuation of the signal and dispersion. The impairments associated with the fiber had a special significance in this chapter, since this element is characteristic for providing a high amount of limitations especially in terms of transmission distance due to attenuation of the signal and dispersion.

Chapter 3. Impact of the optical interface in ROF systems

3.1 – Performance assessment

As described in previous sections, there are several optical impairments related to the components which are used in an optical link, that may affect the radio signals that modulate (directly or external) an optical carrier, travel on a fiber (with or without amplification) and are detected. It is important, within RoF context to identify those impairments and assess their impact, in a practical way. To assess the impact of the several optical components we will perform the following experiments. In order to help understanding the concepts involved in the experimental work that will be explained later in, some essential points have to be clarified. The RF signal used throughout the work a UMTS signal (Universal Mobile Telecommunication system), in the UMTS communications there are two distinct frequency bands: uplink and downlink, both frequencies have a bandwidth of 60 MHz, centered at 1.95 GHz and 2.14 GHz respectively [ETSI, 2008], as shown in figure 3.1, this enables the terminal equipment to send and receive at the same time, because different frequency bands are used for downlink and uplink. Both the frequency band for uplink and downlink are divided into 12 channels with a bandwidth of 3.84 MHz, and a 5 MHz separation between channels [ETSI, 2008] (figure 3.2). Throughout this work we will focus only on the downlink.

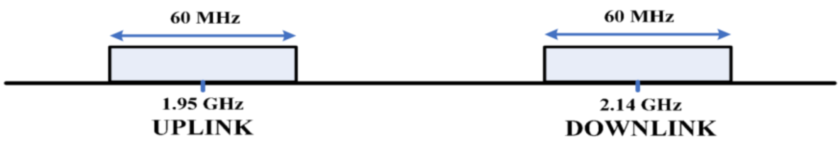


Figure 3.1 -Uplink and downlink frequency bands in a UMTS signal [ETSI, 2008]

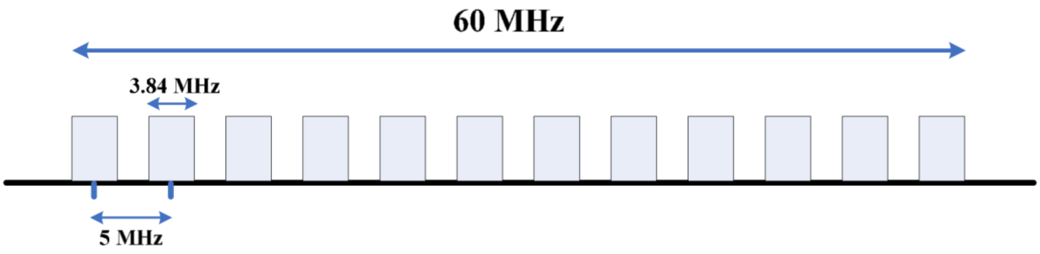


Figure 3.2 -Uplink and downlink frequency bands constitution [ETSI, 2008]

Another important concept is the EVM (error vector modulation) measurement. The performance measure is the error vector magnitude (EVM) of the signal received that according to ETSI (The European Telecommunications Standards Institute) “is a measure of the difference between the theoretical waveform and a modified version of the measured waveform (...)” [ETSI, 1995]. Basically it consists in a vector that measures the difference between the theoretical position of the constellation point that we should get, and the actual position obtained, a graphic demonstration is showed in figure 3.3.

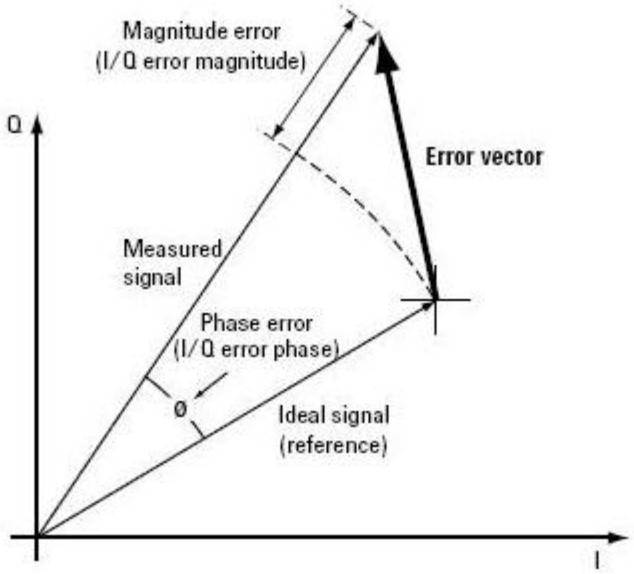


Figure 3.3- EVM demonstration

For most RF signals possible to transmit through an optical link it is set a limit to the EVM in the received signal. Most important RF signals properties used in the experiments are displayed in Figure 3.4. It is important to notice that the performance metric used is the EVM that should be under the imposed limits, to achieve signal detection in good conditions, as shown in the table below.

	UMTS - 3G	WLAN	WIMAX
Standard		802.11g	802.16d
Physical layer mode	WCDMA-3GPP	OFDM	OFDM
Modulation	QPSK	64 QAM	QPSK ¾
Bit rate (Mbps)	3,84	54	15
Limit for EVM (%)	12	5,62	1,41

Figure 3.4 - EVM limit for three RF signals [ETSI, 2008]

By examining the table above the limit for obtaining a signal with a certain quality factor for a UMTS signal type is 12%.

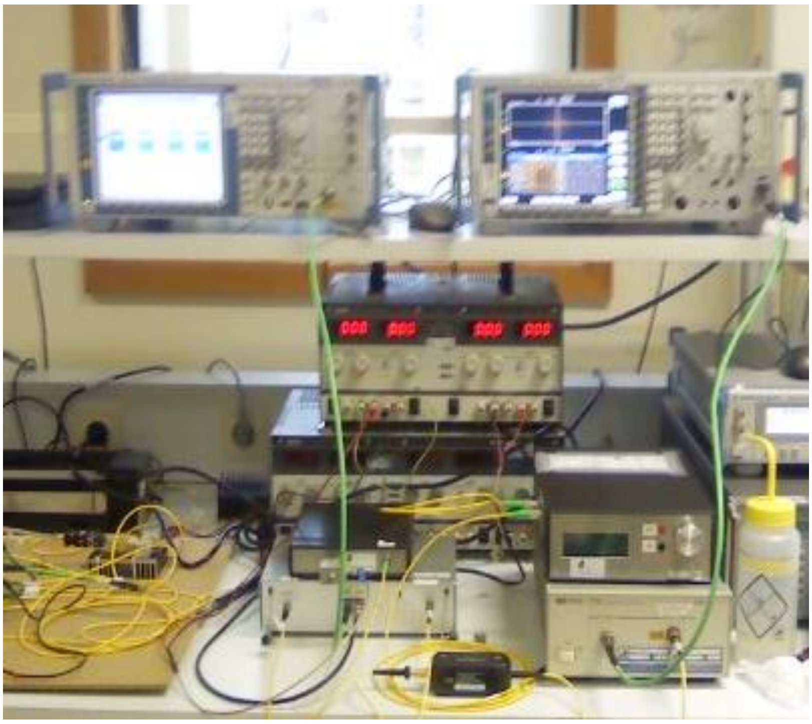


Figure 3.5 - Experimental components used

In the upper left section is the Rohde & Schwartz generator, used to generate the RF signal, in the upper right section the Rohde & Schwartz signal analyzer, used to get graphics and values such as EVM, Frequency spectrum, below the items described before in the centre is the polarization signal generator used to polarize the laser or the external modulator as needed, in front of the polarization signal generator are the laser and the external modulator (below), in the right down side going from up to down we have the SOA amplificator and the photo-detector.

3.2- B2B transmission

3.2.1- Direct modulation

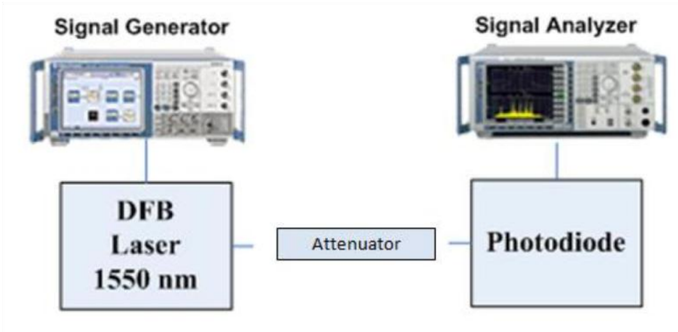


Figure 3.6 - Direct modulation setup

An Ibias = 17 mA was set and the power of the radio signal (UMTS) was varied from -20 dBm to 0 dBm. Results like EVM, power of the detected radio signal and power relation between main/adjacent channels were observed. In figure 3.7 it is possible to observe how the RF signal and the polarization signal were coupled into the laser creating direct modulation.

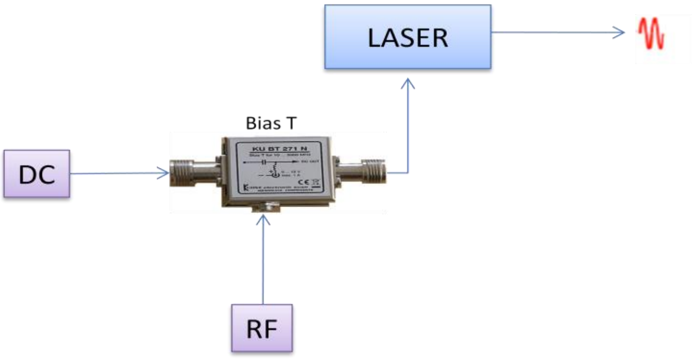
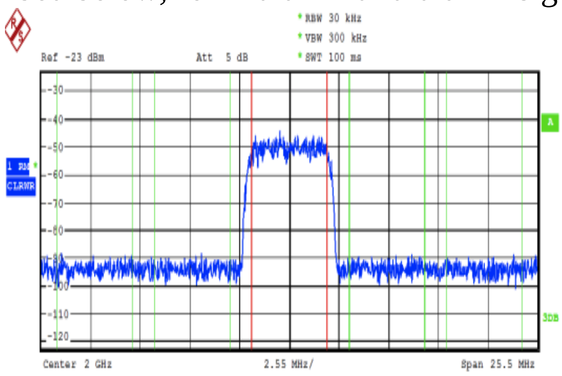
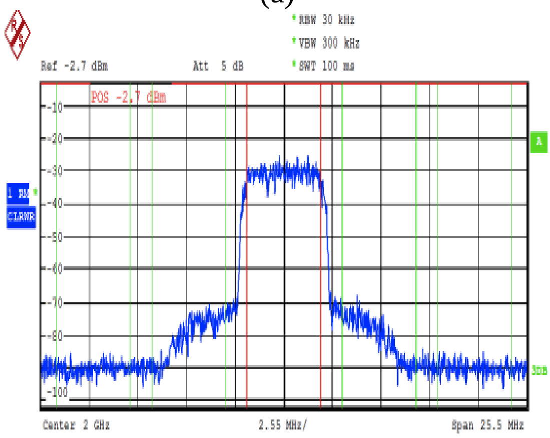


Figure 3.7 - Direct modulation scheme

Some results are described below, for -20 dBm and 0 dBm signal powers:



(a)



(b)

Figure 3.8 - Frequency spectrum for: (a) -20 dBm, (b) 0 dBm signal power

Analyzing the spectrum for the -20 dBm signal, we can verify that the received signal have enough quality, since we cannot identify any sign of significant interference by analyzing the spectrum. For 0 dBm power, it is possible to observe frequency bands adjacent to each side of the carrier, also referred as spectral regrowth, this are features that are introduced by intermodulation distortion, it consists in frequency sidebands that extend to the adjacent channels introducing distortion in the signal.

In the table below are the EVM results for three RF signal powers tested,

Signal power (dBm)	EVM (%)
-20 dBm	0.8%
-10 dBm	0.4%
0 dBm	7%

Table 3.1 - EVM vs. Signal power

As seen in section 2.2.1.3, the laser requires a minimum current to start working and therefore emitting (spontaneous emission), this current is the minimum current threshold ("threshold bias current"). Above this threshold the linear operation area of the laser starts. For very high levels of power input signal, the laser suffers a clipping effect (See section 2.2.1.3), which leads to a significant increase of distortion, and consequently considerably deteriorating the EVM. The expected results regarding to EVM, were that with the increase in signal strength, the EVM continually kept improving, looking at the results table above, we can see that what happens in practice is that for 0 dBm value (higher power), the EVM worsened significantly which indicates at this power value the existence of the clipping phenomenon. Clipping effect in this experimental setup is a limiting factor in terms of signal performance, clipping produces a high level of distortion that is reflected in the received signal and therefore make the EVM much worse (which is higher).

3.2.2 - External modulation

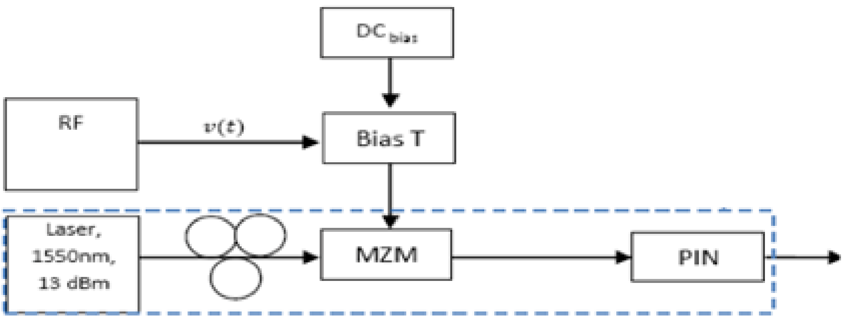


Figure 3.9 – External modulation setup

An Ibias of 30 mA was set, and it was considered P_{UMTS} = - 10dBm. The objective was to obtain EVM, and signal detection and relationship power between the main channel/ adjacent to different values of Vbias.

The obtained results were,

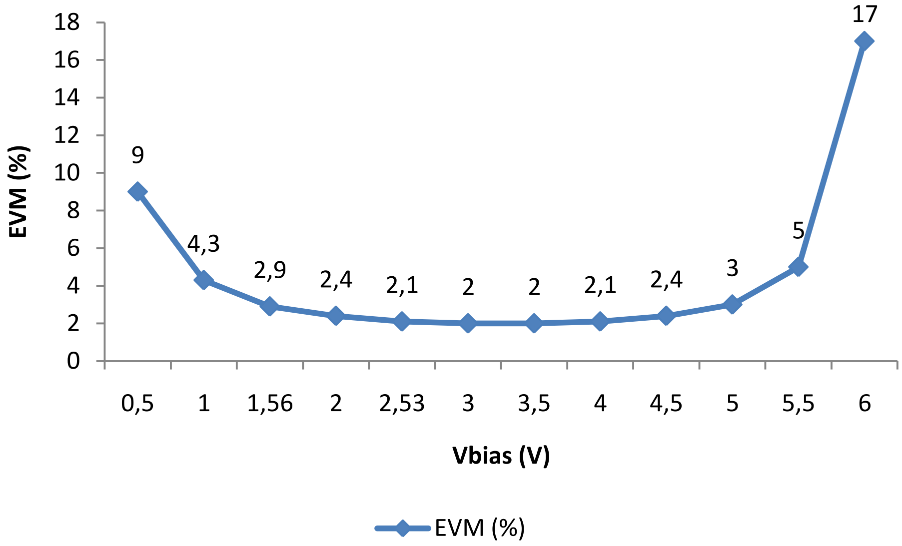


Figure 3.10 - EVM variation with Vbias

Observing the results obtained above, we can see from the graph in figure 3.10 that there is an improvement in EVM until approximately 3.5V and then the EVM increases significantly. This phenomenon indicates that the Mach-zehnder device need to be polarized just 50% of the curve of the waveform in order to have a signal at the output with virtually no distortion, if the polarization is upper or below this level variations of the phase of the signal will occur and distortion is introduced into the signal (see section 2.3.2.1.1) increasing EVM, and consequently decreasing system performance.

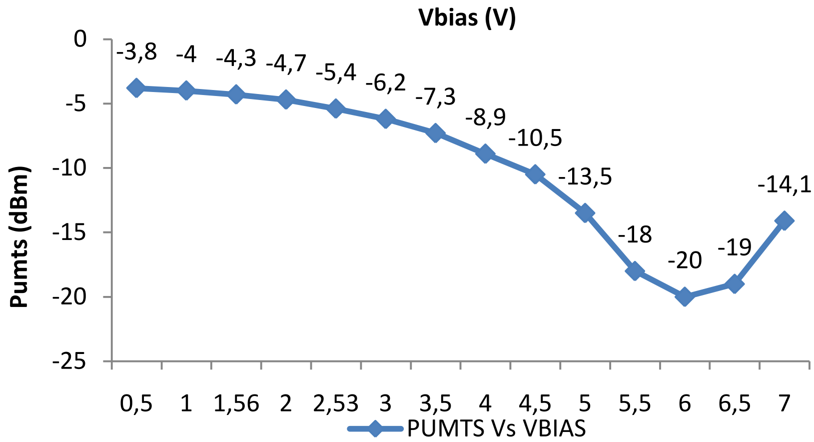


Figure 3.11 - PUMTS vs VBias

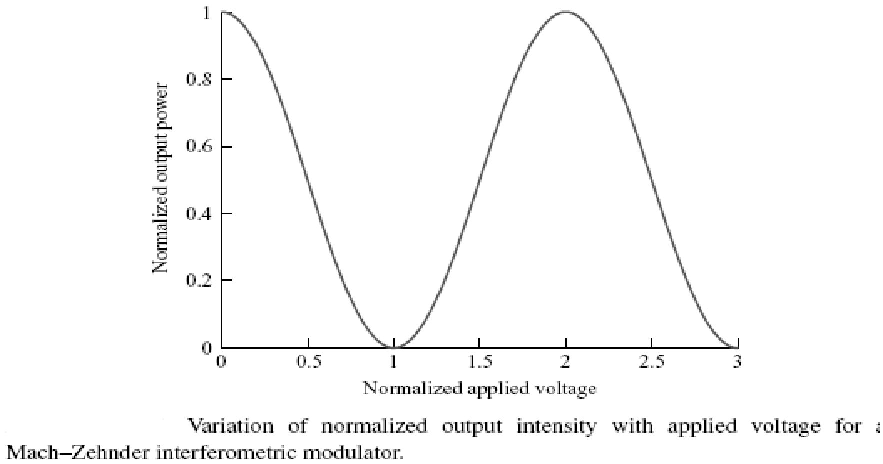


Figure 3.12 - Theoretical waveform for MZM output

Looking at the graph of average power as a function of bias voltage (figure 3.11) we can see that as expected theoretically (figure 3.12) this is a very similar waveform, we can observe that the values at 50% of the curve are roughly between 3.0 V and 3.5V and the lowest EVM was obtained for those values, indicating that the signal has less distortion has expected.

3.3 – Transmission over fiber

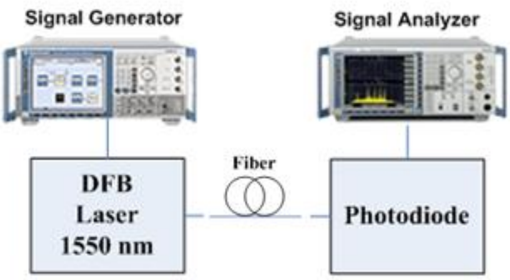


Figure 3.13 – Experimental setup with optical fiber

For this experiment 40 km of SMF were introduced in the setup, and a PUMTS of -5 dBm was adjusted. Two situations were tested, transmission with direct modulation and external modulation. For the direct modulation one, an Ibias of 28 mA was set, the resulting Psignal/adjac and EVM were evaluated. With external modulation an Ibias of 35 mA was set and the MZM was biased with 5.5 V. Table 3.2 show the obtained results for the two types of modulation,

	Psignal/adjac	EVM (%)
Direct modulation	-18dBm/-49 dB	0.7%
External modulation	-39dBm/-41dB	1%

Table 3.2 – Optical link experiment results

The system performance is approximately similar to the B2B case, showing that the tested system is robust to fiber dispersion and non-linear phenomenon’s. Theoretically due to almost null chirp in the external modulation case, an expected result was a better EVM result than for the direct modulation situation. As it can be observed in table 3.2 the direct modulation has a better EVM value, and thus better performance. Comparing the obtained results, in the case of direct modulation a factor to consider is signal chirp (see section 2.2.1.1), which will degrade the signal, as said previously due to lower chirp it was expected to obtain better results of EVM for external modulation, however there is another parameter to take into account who will judge the outcome, the EAM (AM efficiency see section 2.2.1.2) in addition to chirp.. In the case of external modulation the efficiency is lower than the AM case of direct modulation, regardless of not having chirp this phenomenon will also have an important role in the implementation of more or less distortion in the signal.

3.4 Amplified optical link

An Ibias = 17 mA was set and varied to power radio signal (UMTS) -20 dBm to 0 dBm, the EVM, relation between power between the main channel/adjacent, were observed, now with the difference of a SOA in our setup.

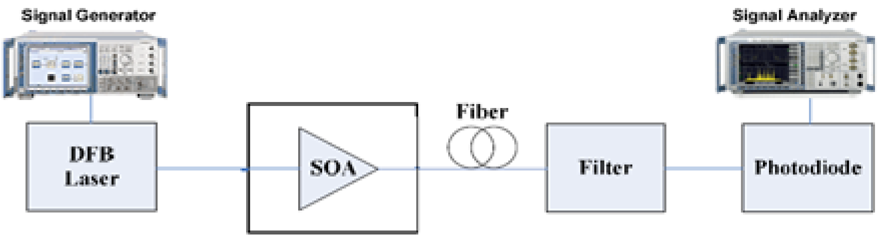


Figure 3.14- Experimental Setup

In this case the SOA pump laser was off, for a bias current of 17 mA the laser output power is approximately 0 dBm and therefore our amplifier is already in saturation.

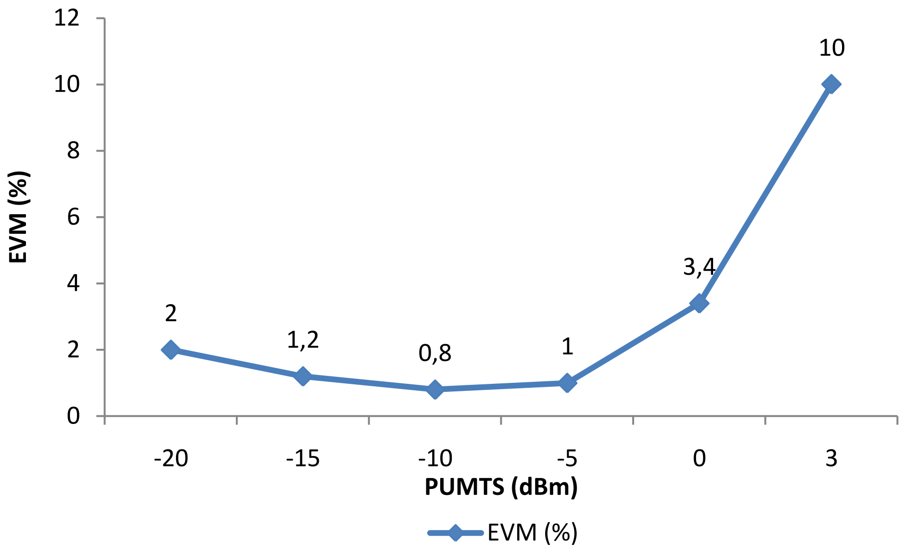
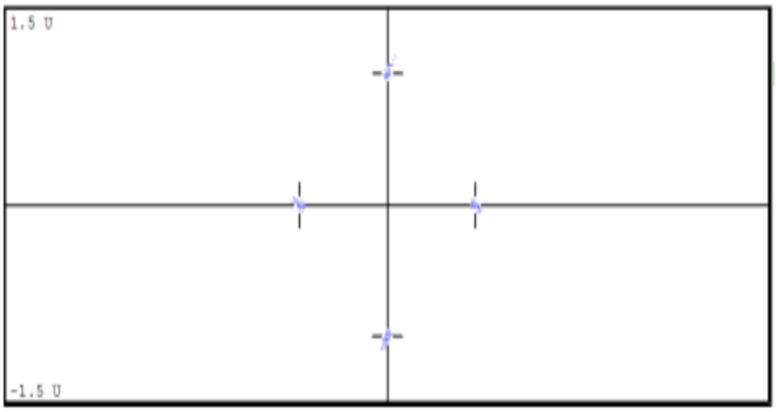
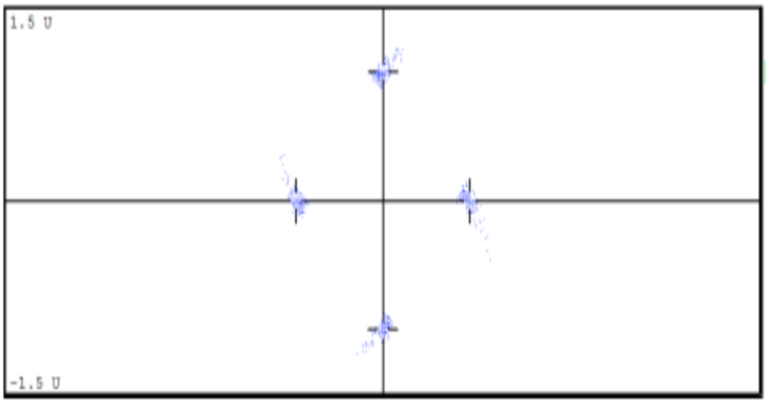


Figure 3.15 - EVM variation with PUMTS

Figure 3.15 shows the EVM variation increasing RF signal strength. With the increase of RF signal power an improvement of SNR is obtained, it would be expected that as we were increasing the power of the signal, the EVM was always decreasing, that didn't happened in practice, SOA introduces variations of the phase and amplitude (see section 2.4.1, 2.4.2), where these changes are a direct reflection of the input signal. It is easy then to conclude that there is a commitment to take into account, increasing UMTS signal strength improves SNR, but then increases the repercussion of the nonlinearities introduced by the SOA in the output signal. As depicted in figure 3.15, from -5 dBm, the EVM starts increasing reaching values near his limits for 3 dBm, confirming what has been explained. In Figure 3.16 (a) and (b), it is possible to observe the constellations obtained for PUMTS=0 dBm and PUMTS=3 dBm,



(a)



(b)

Figure 3.16 – Received constellations for (a) P_{UMTS} = 0 dBm, (b) Constellation for P_{UMTS} = 3 dBm

Observing the previous figures, there is an evident degradation of the signal, in case a PUMTS = 3 dBm was used, introducing a significant distortion to the signal, due to an enhancement of the SOA non-linearities, resulting in more dispersed points.

3.5 Conclusions

This chapter focused on the confirmation and testing of some impairments discussed in chapter 2, in an experimental way. As it was possible to observe in previous experiments, each solution can have different approaches in order to obtain the best performance, in most situations employing external modulation is a better choice, but not always, when data rates are in the low gigabit range and transmission distances are less than 50 km or so, directly modulated lasers are the best solution due to their better efficiency when modulating data, that overcomes the limitations due to frequency chirping. As seen several impairments, such as laser clipping, fiber distortion, SOA non-linearities, gain saturation, noise figure, external modulator non-linear behavior, have an important impact in ROF systems performance.

Chapter 4. Optical frequency multiplication in RoF systems using MZM in nonlinear regime

4.1 Introduction

The purpose of this chapter focuses on the presentation and discussion of simulations using VPI Transmission Maker software, with the scope to test some of the limitations associated with the distribution of RoF signals through optical links discussed in chapter 2. Simultaneously another objective is to test the use of nonlinear properties associated with the Mach-Zehnder external modulator discussed in previous chapters in order to obtain frequency multiplication. Several simulations were realized in order to analyze the described situations, using frequency multiplication, amplitude modulation and direct detection, and orthogonal frequency division multiplexing (OFDM) modulation format.

Efficient and cost effective methods of generating and transmitting microwaves and mm-waves are extremely important to follow the growing trend of wireless communications. As previously mentioned (chapter 2), one of the biggest advantages associated with the use of optical fiber as an mm-wave and microwave signal transmission medium lie in the almost unlimited bandwidth and very low propagation loss, due to this the generation and transmission of this type of signals over an optical fiber have been investigated for various applications in an arduous way [Li, 2010][TSANG, 2009]. The biggest challenge has to do with the generation of mm waves above 40 GHz, since most of LiNbO3 Mach-Zehnder modulators have frequency responses typically below this frequency, and most of the equipments required to the optical link are very expensive for frequencies above 40 GHZ [Qi, 2009]. Because of these factors a great interest in cost effective ways of generating mm-waves and microwaves for higher frequencies (>40Ghz) exists. In a RoF system, to simplify the implementation and to reduce associated costs it is desirable that a high-frequency microwave or mm-wave to be generated directly in the optical domain [Yu, 2006] and a low-frequency RF signal can be up converted to a high-frequency signal in the mm-wave band by mixing it with an optically generated mm-wave.

In order to obtain a high-frequency signal from a low-frequency RF signal a technique was used based on frequency doubling using a Mach-Zehnder modulator (MZM) that is dc-biased at the peak output power to suppress the odd-order sidebands [Rujian, 2009] [He, 2009] . In all the setups presented later in, the modulator used is a single arm Mach-Zehnder with a power transfer function that can be approximated by

$$\mathbf{f(Vbias) = E_o sin^2(A\ Vbias)} \quad (4.1)$$

where E_o represents the laser power, Vbias the modulator biasing voltage and A is the amplitude of MZM driver voltage. It is possible to decompose the equation in its Taylor power series expansion to obtain a representation that allows isolating each of its members, the Taylor power series expansion for the previous equation using b=AVbias as the expansion point is,

$$f(Vbias) = E_o sin^2(b) + E_o \sin(2b)\,(Vbias - b) + 2E_o \cos(2b)\,\frac{(Vbias-b)^2}{2!} - 4E_o \sin(2b)\,\frac{(Vbias-b)^3}{3!} \quad \mathbf{(4.2)}$$

Observing equation 4.2 it is possible to identify the first, second and third order components, the objective being maximizing the second order component and minimizing the other components to achieve frequency duplication at the MZM output. In order to identify the optimal bias point which allows the aforesaid it is necessary to superimpose the waveforms of the various terms of the equation in order to see where the second term suffer maximization and minimization of other components, figure 4.1 shows the results,

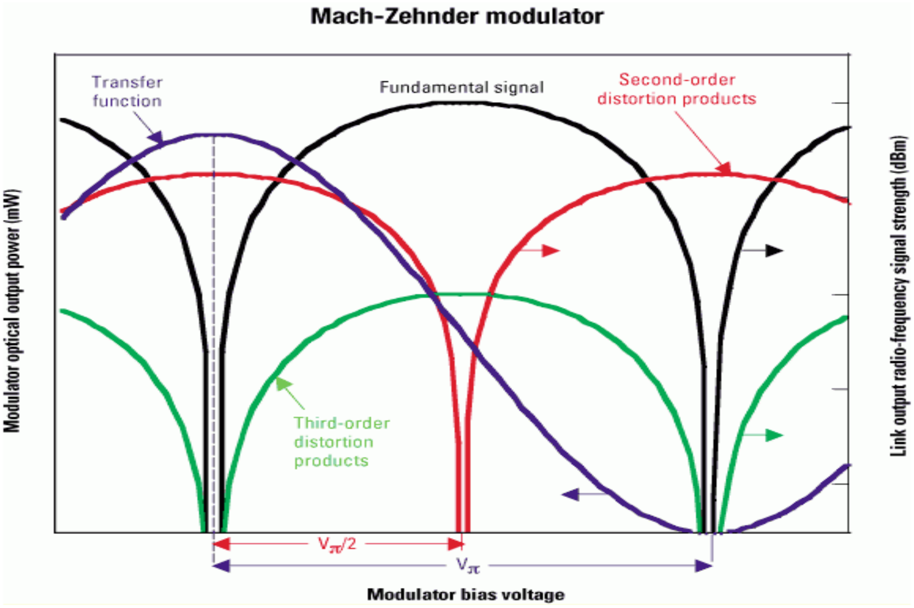


Figure 4.1 – Mach zehnder modulator waveforms.

As it can be seen through the figure above the optimal bias point which allows duplication of frequencies by minimizing the terms of odd order is for Vbias = π, being the bias point used in all the simulations that will be presented later in.

4.2. OFM considering amplitude modulation

Amplitude modulation means that information is modulated onto the amplitude of the optical signal, which is proportional to the signal's instantaneous power. The detection method used in these systems is direct detection, which means that the receiver detects the instantaneous power of the received signal. This type of system has been widely used in both fiber and free-space optical communication systems.

4.2.1 Double side band

The first setup tested is presented in figure 4.2, it consists of a system which performs amplitude modulation of a signal at 10 Gbps mixed with an RF carrier at 20 GHz, modulated by an optical signal provided by a DFB-LD with an operating frequency of 193.1 THz, the resulting modulated signal is devoid of its optical carrier through an FBG filter (Fiber Bragg Grating) and subsequently detected by a PIN, filtered with a LPF the clock being recovered so that the eye diagram can be observed, among other parameters. The most important adjusted parameters are in table 4.1,

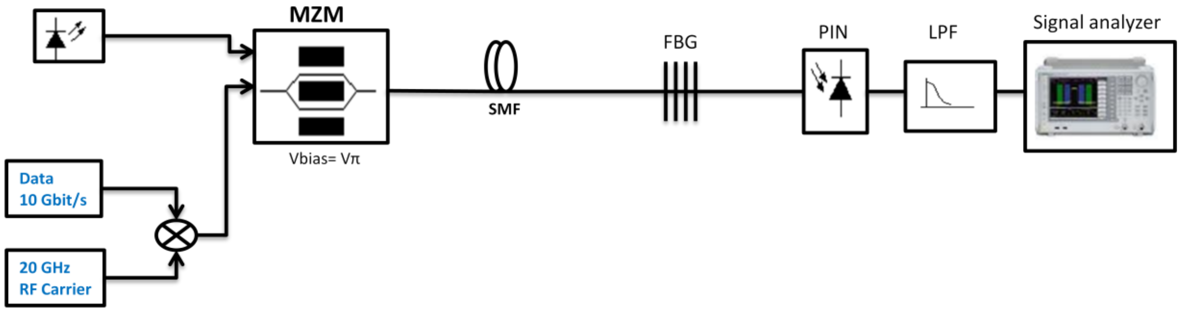


Figure 4.2 –frequency duplication setup

Data	NRZ Pseudo –random bit sequence with word length 2^7-1 Default BitRate: 10 Gbps
Electrical signal	20 GHz RF carrier: input volt. 1V
Mach zehnder modulator	Extinction Ratio : 30 dB Bias voltage: 3.1 V Bias amplitude : 1.0 V
CW DFB Laser	Wavelength: 1553.6 nm Lasers CW Power: 0 dBm Linewidth: 10 MHZ
SM Fiber	Fiber loss: 0.2 dB/km Fiber Dispersion=17 ps/(km.nm)
Filter FBG	Bragg Resonance Freq. :193.1 THZ Rejection : 30 dB Filter Bandwidth: 20 GHZ
PIN	Responsivity: 1 A/W Thermal Noise:$1x10^{-12}$ A/$\sqrt{Hz}$ Shot noise: On

Table 4.1 – Setup Parameters

The purpose of this simulation is to test the possibility of obtaining frequency multiplication using amplitude modulation and direct detection. An FBG filter is used to suppress the optical carrier. The spectrum before the FBG is shown in Figure 4.3. It can be seen that the generated optical mm-wave mainly has three tones with frequency spacing of 40 GHZ, the baseband signal and the 40 GHz RF component. After suppressing the optical carrier the two strong components separated by 4x*fm* impinge on the photodiode, to generate an mm-wave signal with frequency equal to 4x*fm*. In other words, the drive frequency is quadrupled.

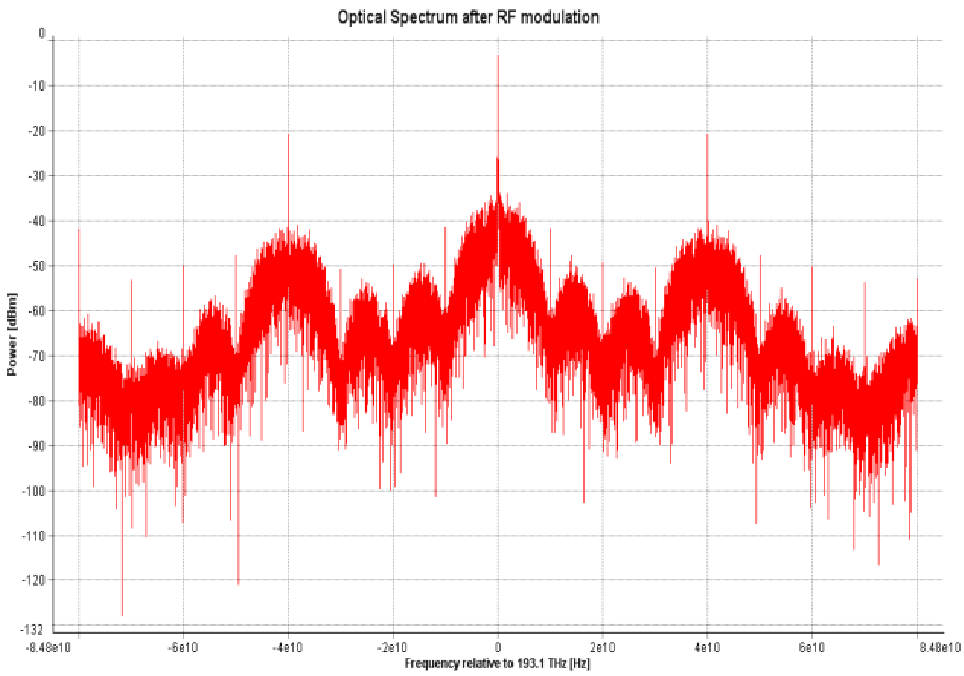


Figure 4.3 – Optical Spectrum after MZM

The optical spectrum after the FBG is presented in figure 4.4, it is possible to observe the absence of the optical carrier at 193.1 THz, and the two main tones with a frequency spacing of 4x*fm*

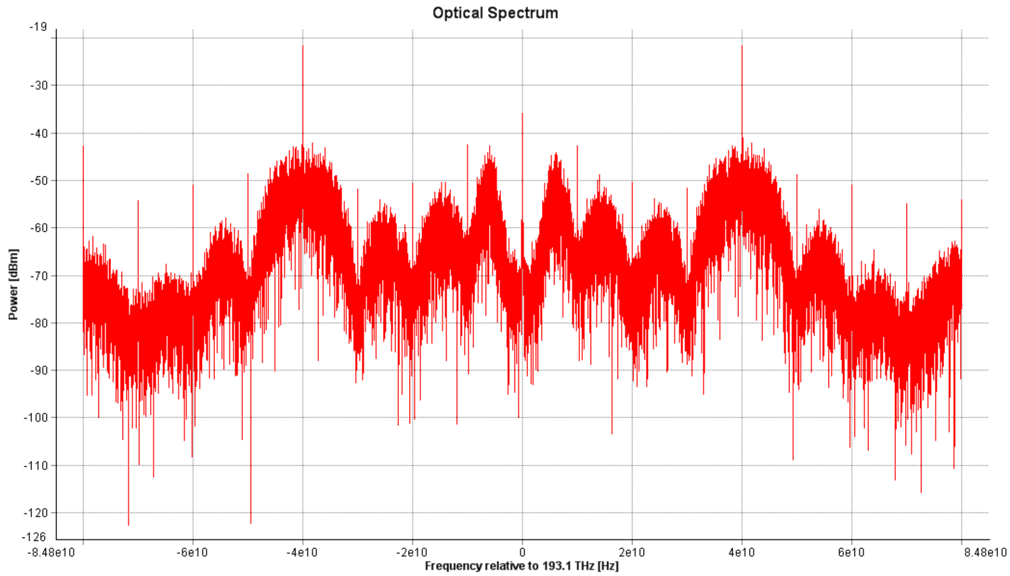


Figure 4.4 – Transmitted optical spectrum at FBG filter

As it is possible to observe from figure 4.3 and 4.4, the frequency of the LO used at the CO was successfully doubled resulting in a 40 GHZ signal, and using the spacing between the two sidebands frequency quadruplicating is achieved. In order to check the validity of the system several tests were performed. Figure 4.5 presents the BER evolution with the variation of the laser power at the CO,

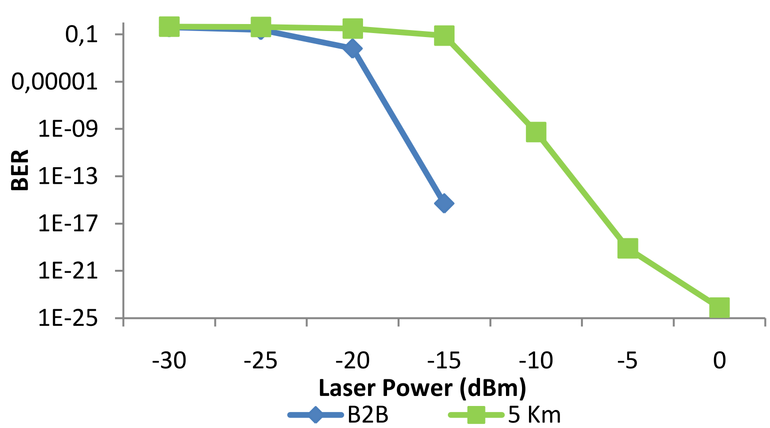


Figure 4.5 – BER vs. laser power for B2B and 5 km of SSMF

Laser Power was varied from -30 dBm up to 20 dBm, and the impact in system performance was evaluated, the optimal power is 0 dBm. The results show that system BER improves considerably increasing the transmission power up to 0 dBm for both cases (B2B or with 5 km of SSMF), for higher powers the received signal is error free for B2B. Using 5 km of SSMF decrease the performance as expected, the maximum transmission distance achieved is about 7 km (fig. 4.7). Slightly better results were obtained using laser powers above 0 dBm, but it is not the better option as with the use of optical fiber, high power levels cause an enhancement of fiber nonlinearities.

Another parameter that have an important impact in modulation performance and thus system performance, is the RF signal power, in order to achieve an optimization the RF power was varied and the respective BER values were collected, using a bit rate of 10 Gbit/s and an optical power of 0 dBm in a back-to-back system, figure 4.6 show the results,

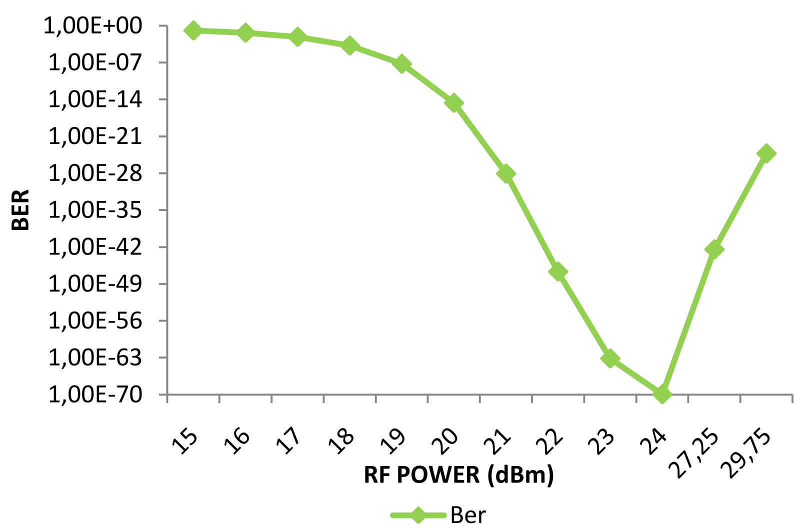


Figure 4.6 - Ber vs. RF power

Figure 4.6 presents the BER variation for different RF powers, an improvement is obtained from 15 to 24 dBm, for values higher than this, system performance is worst as it can be observed (BER increases again). The optimal Ber results were obtained for an RF power of 24 dBm, thus from 20 dBm on the system is practically error free, so a RF power of 20 dBm is enough to achieve the ideal performance, this value was used for next tests.

The maximum transmission distance was tested using the adjusted optimal power (0 dBm) and RF power, for two different bit rates, respectively 10 Gbit/s and 20 Gbit/s, the results are presented in figure 4.7,

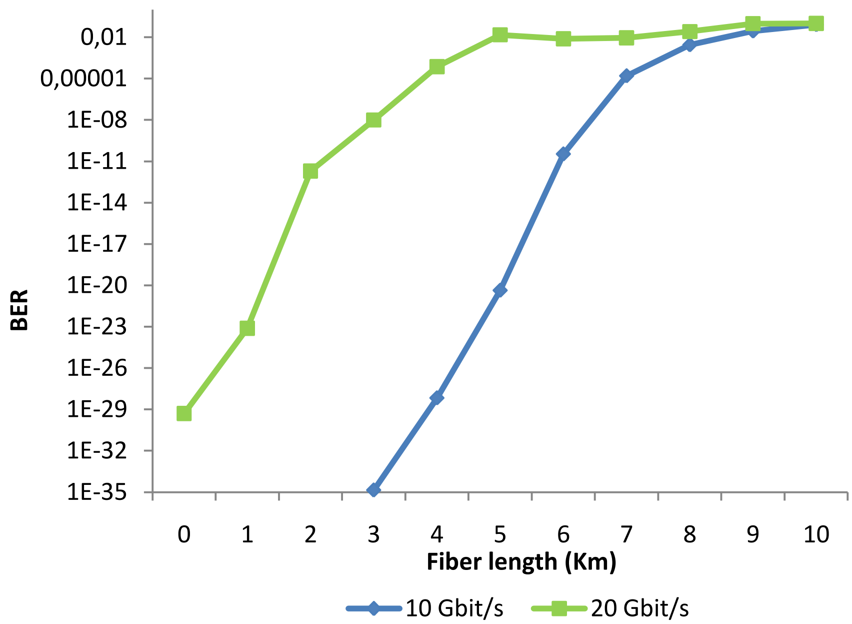


Figure 4.7 - BER vs. Fiber length for 10 Gbit/s and 20 Gbit/s

The transmission distance achieved is around 7 km for the 10 Gbit/s signal, and 4 km for the 20 Gbit/s one. For a 10 Gbit/s bit rate, the system is error free up to 3 km fiber distance. The system has worst performance as expected with a 20 Gbit/s bit rate, due to more susceptibility to fiber dispersion, but the system is capable of handling this bit rate and transmitting along SSMF, with an acceptable performance.

4.2.2 Carrier suppressed double side band

In this section another approach is made to obtain optical frequency multiplication, with an optical carrier suppression modulation technique, which has will be seen later has a better performance, and the advantage of being transparent because in this case no filtering is needed between the CO and the BS, due to the optical carrier being directly suppressed in the modulation operation. The simulated setup is described in figure 4.8, two Mach-zehnder modulators are used in order to achieve carrier suppression, and a schematic showing the waveforms in each point of the carrier-suppressed modulator is described in figure 4.9.

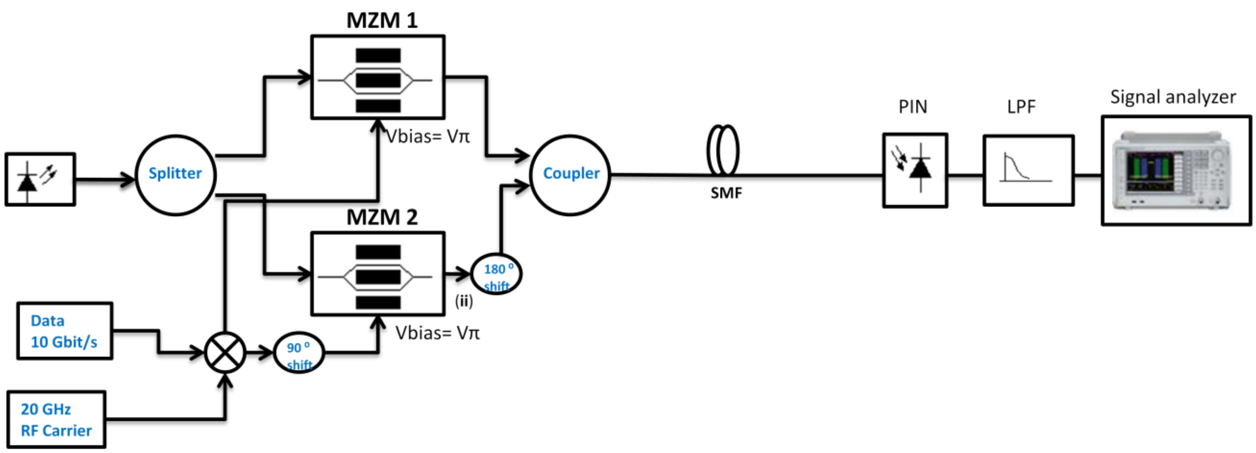


Figure 4.8 – Carrier suppressed setup

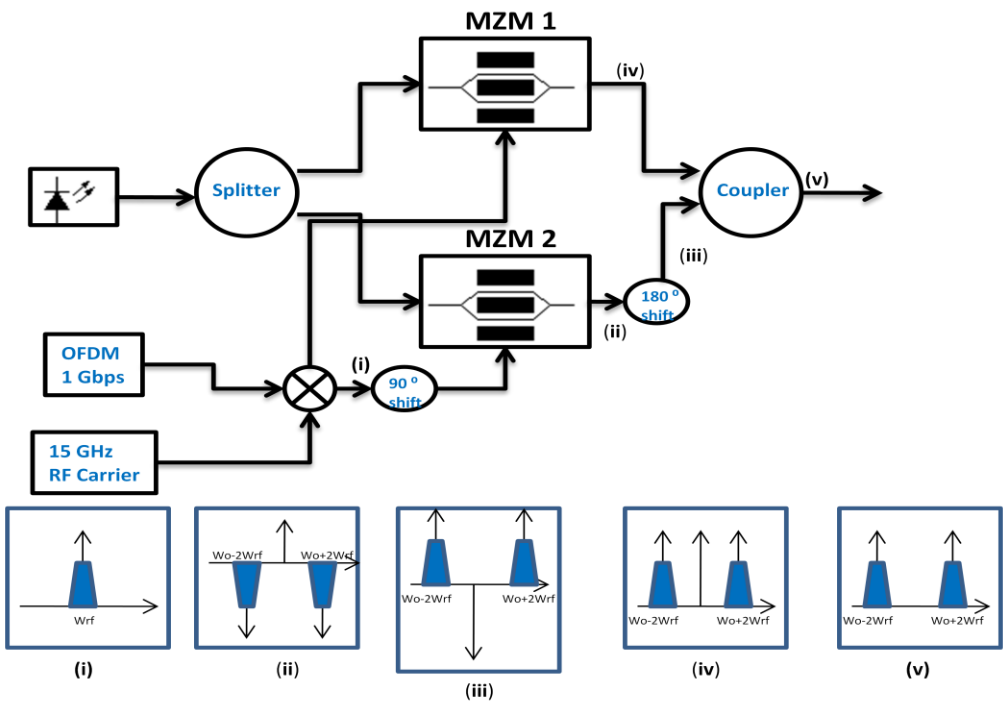


Figure 4.9 – Waveforms at each point of the modulator

The multiplication concept used in this simulation is based on what was explained in section 4.1, the parameters of the link components are similar to those presented in table 4.1, the frequency multiplication is obtained by polarizing the MZMs at Vbias = Vπ, the difference is in the way the optical carrier is removed. Figure 4.8 shows the principles of the proposed optical signal generation system based on frequency quadrupling. The optical field at the input is split into two arms that are the inputs of two single arms Mach-Zehnder modulators. The field at each branch may be expressed by $E_{in1}(t) = E_0/\sqrt{2}\cos(\omega_c t)$ (4.3), and $E_{in2}(t) = E_0/\sqrt{2}\cos(\omega_c t + \Delta\phi)$ (4.4) where Eo and ωc are respectively the field amplitude and the carrier frequency, and $\Delta\boldsymbol{\phi}$ is the relative phase shift. Two Mach-Zehnder modulators (MZM) produce the amplitude modulation of the optical carrier. These modulators are driven with the same RF signal with a phase difference of $\frac{\pi}{2}$. The driving RF signal is single-tone, the resulting output of the MZM can be expressed as $E_{out}(t) = E_{in_n}(t)\cos\left(\frac{\pi}{2}\frac{V_{DC}}{V_h} + \frac{\pi}{2}\frac{V_m}{V_h}\cos(\omega_m t)\right)$ (4.5) VDC is the bias voltage driving the Mach-Zehnder modulator, V_m and ω_m the amplitude and angular frequency of the electrical signal, and V_h the half-wave voltage [Frenkel, 1998].

As we can see in fig. 4.9 (iii) the output of the MZM2 is shifted by π when compared with MZM1 output, but the optical carrier has the same orientation as no shift was induced to it, so by shifting MZM2 output by π, as seen in fig. 4.9 (iv) the spectrum is identical to the one at MZM1 output with the important difference of the optical carrier having opposite phase, when the two outputs are coupled together optical carrier undergoes a destructive interference being removed of the resulting signal (fig. 4.9 (vi)).The spectrum of the obtained signal is showed in figure fig 4.9,

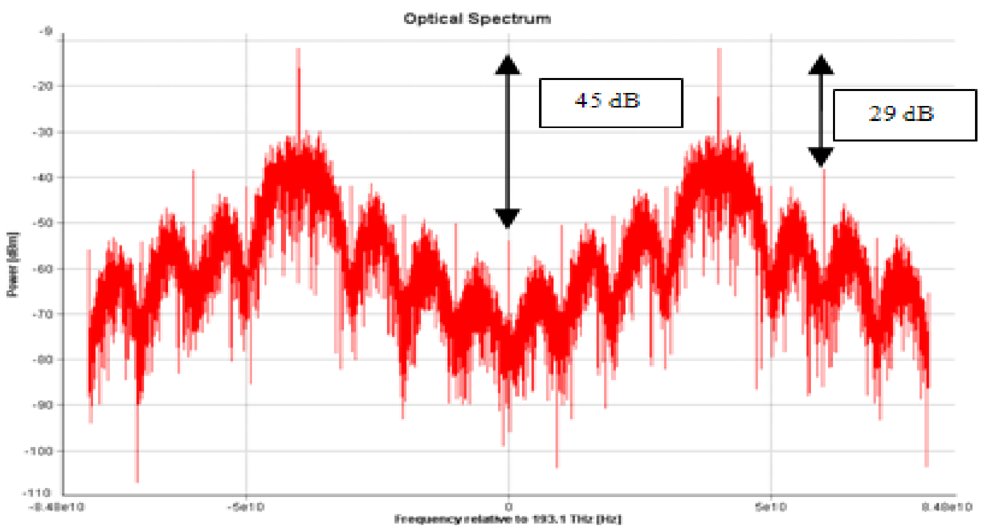


Figure 4.10 – Spectrum with optical carrier suppression

Observing the previous figure, the carrier suppression ratio with respect to the f0+2fm and f0-2fm components was 45dB. The suppression ratio of the other components was 29dB, where f0+3fm and f0-3fm components were most significant. The third order components are due to nonlinearity of optical modulation.

In order to verify the performance of this system, several tests were carried out. Similarly to what was done in the previous section, the BER value was evaluated for different laser powers for B2B and for 5 km of SSMF, figure 4.11 show the results,

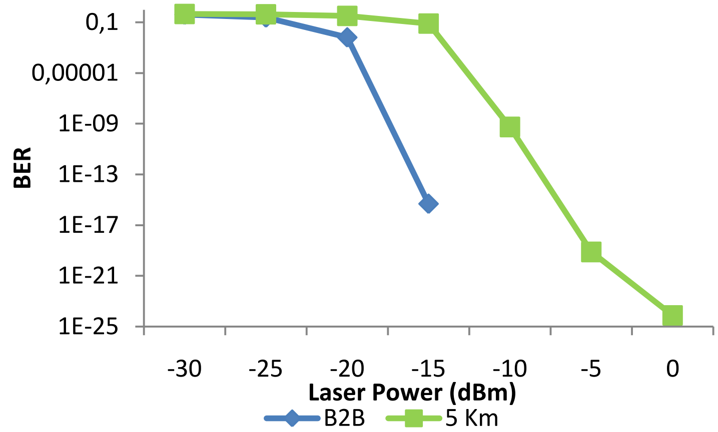


Figure 4.11 – BER vs. Laser power for B2B and 5 km SSMF (C.S CO)

The input power at the CO was varied from -30 to 0 dBm, for B2B the system behavior improves considerably from -15 dBm being error free for higher laser powers. When the system is connected in B2B, a laser power of -15 dBm is enough, but to achieve good results with the signal travelling along optical fiber a higher power must be choose, due to this fact the optimal laser power is 0 dBm, and next simulations of this system were performed with this value. Similarly to which was made in previous section the RF signal power impact was tested, using the optimized parameters in a back-to-back scenario, the graphic is depicted in figure 4.12,

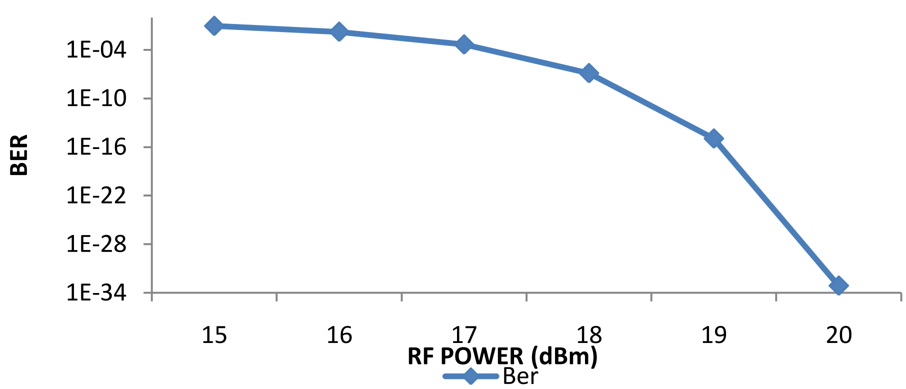


Figure 4.12 – BER vs. RF signal power (C.S CO)

As in the previous situation (see section 4.2.1), the system was error free for RF powers higher than 20 dBm. Analyzing both graphics (fig. 4.11, fig. 4.12), it is possible to see that this approach using carrier suppression present better BER values (and thus best performance). Figure 4.13 presents BER variation with fiber distance,

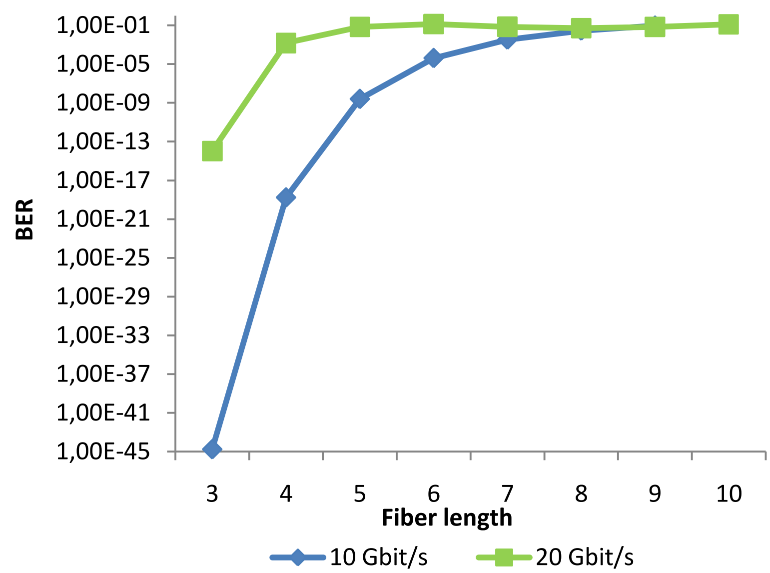


Figure 4.13 – BER vs. Fiber length for 10 Gbit/s and 20 Gbit/s (C.S CO)

As expected the results show the same evolution observed for the system without carrier suppression, but results are quite better for the case using DSB-CS modulation, the system allows transmission to a maximum distance of 7 km, allowing transmission with higher bit rates up to 20 Gbit/s, and with error free transmission up to 3 km even with 20 Gbit/s. To finalize this section a comparison between the two systems (DSB, DSB-CS) is made in figure 4.14,

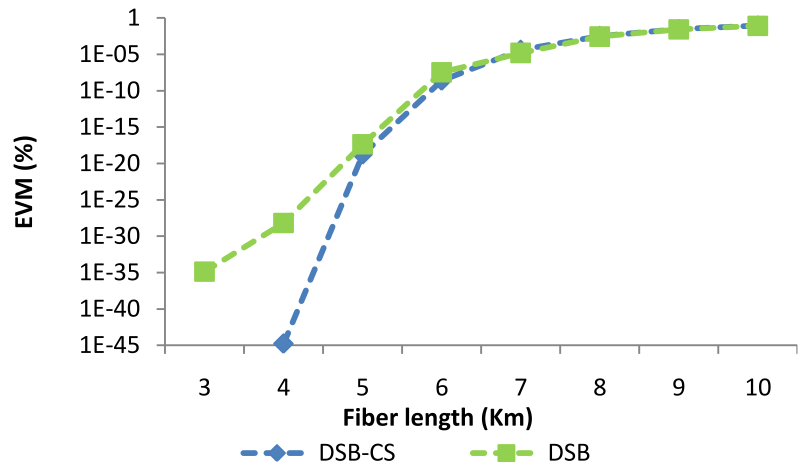


Figure 4.14 – Comparison between DSB and DSB-CS modulation

The previous figure shows the difference between using DSB and DSB-CS modulation in systems with amplitude modulation. It is clearly observable in Figure 4.14 that the solution with carrier suppression has better performance, this is mainly due to the absence of optical carrier that reduces the power level that travels along the fiber and thus the impact of nonlinear effects is not as sharp as in the case where the optical carrier is removed only at the receiver. However such systems do not allow reuse the optical carrier for uplink transmission, needing more complexes and expensive BS if the system need to support uplink data transmission, due to this fact a study of the pros and cons of each technique must be done to achieve the most appropriate solution for each situation.

4.3 OFM considering OFDM modulation

Chapter 4.2 presents two methods of generation and transmission of optical millimeter-waves, with a binary on-off keying (OOK) modulation format. Non-return-to-zero OOK (NRZ-OOK) is the simplest optical modulation format for amplitude modulation and direct detection optical transmission systems. The purpose of this section is to present architectures that employ orthogonal frequency division multiplexing (OFDM). OFDM modulation format has widespread utilization in wireless LANs (WLANs), digital broadcasting and broadband access networks, the integration of OFDM and optical wireless techniques makes cost effective solution for broadband wireless access networks.

OFDM is a multi-carrier transmission technique in which a high bit-rate digital stream is split into several narrowband channels at different frequencies, using subcarriers. The subcarriers are modulated using Phase shift keying (PSK) or Quadrature Amplitude Modulation (QAM) and are carried on a high frequency microwave or millimeter-wave carrier [Prasad, 2004]. OFDM technology is one of the advanced modulation techniques for future wireless communications because it provides increased robustness against narrowband interferences and frequency selective fading [Prasad, 2004].

OFDM technology has been widely adopted in ADSL and ROF wireless systems and wireless digital audio and video broadcasting [Proakis, 2005].

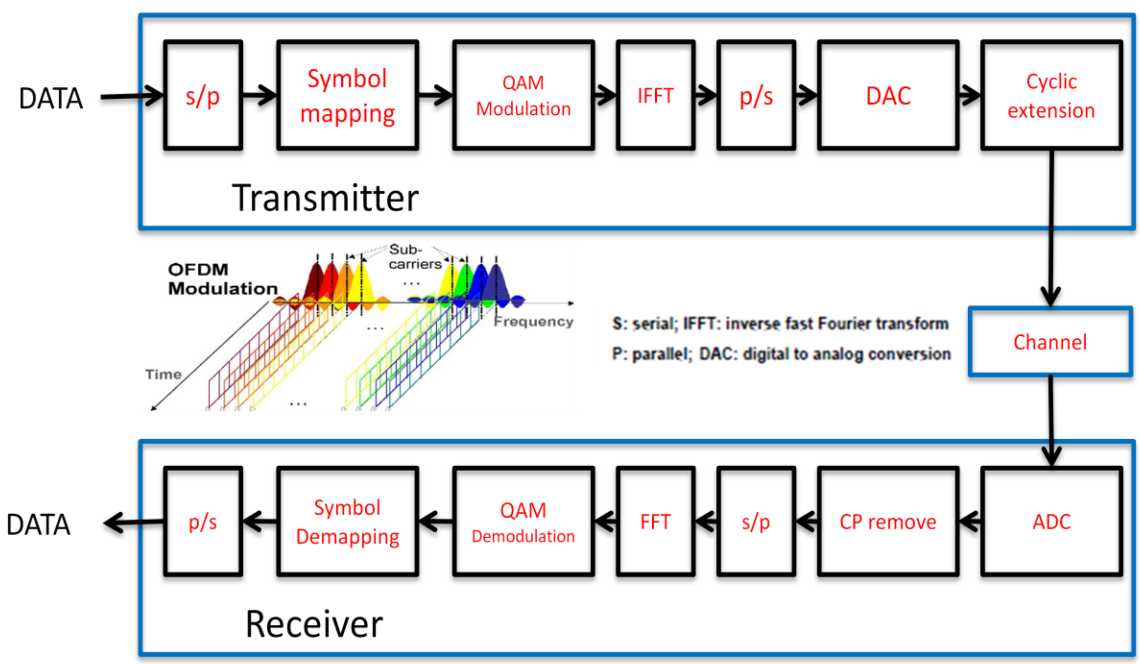


Figure 4.15 Block diagram of an OFDM system.

Figure 4.15 presents an OFDM system model. Data are apportioned at the transmitter in the frequency domain and converted to the time domain using an inverse fast fourier transform

(IFFT). A complex time domain waveform containing a superposition of all the subcarriers is produced, and a cyclic prefix is added to each transmitted block after the IFFT, so that the relative delays between the received OFDM-subcarriers can be accommodated without destroying the orthogonality of the OFDM subcarriers [Proakis, 2005]. In the receiver, an FFT is used to recover the original data.

Optical transmission systems employing OFDM have gained considerable research interest, due to their capability to use higher level modulation formats to increase spectral efficiency and higher robustness to fiber chromatic dispersion, as well as Channel equalization that is a key component in OFDM transmission [Jansen, 2007][Lowery, 2007]. Equalization is used to remove amplitude and phase distortions caused by the channel. Optical OFDM systems in SSMF can be realized either with direct detection or with coherent detection. Whereas direct detection is a cost-effective method, the sensitivity of coherent OFDM is superior to that of direct OFDM at the cost of more complexity [Jansen, 2008]. In the systems presented in the following sections direct detection method is used in order to achieve cheaper systems with an acceptable performance.

4.3.1 Frequency Quadrupler for mm-wave OFDM-UWB signals

The aim of this section is to present and discuss frequency quadrupling techniques for mm-waves generation, where optical subcarrier modulation is used to directly carry OFDM UWB signal.

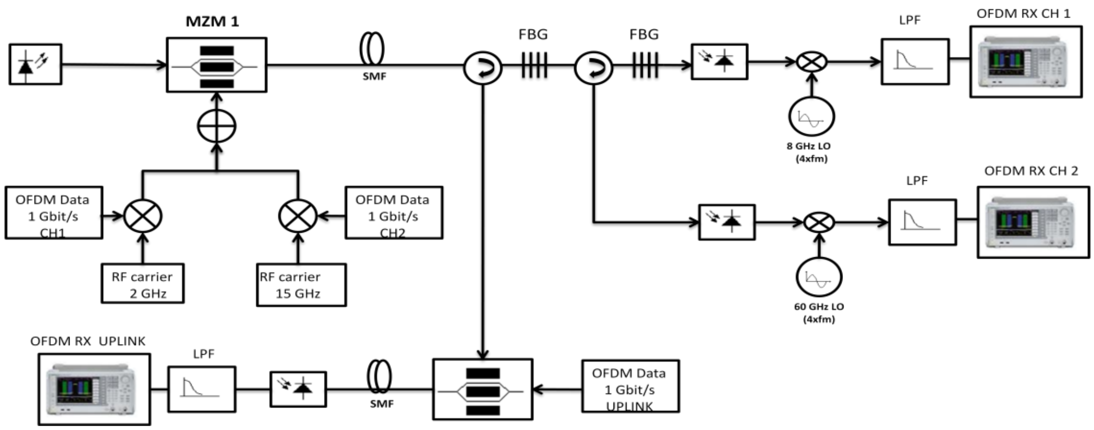


Figure 4.16 – OFDM-ROF system architecture

The schematic of the ROF link simulated is shown in Figure 4.16. The OFDM signal is generated with a bit rate of 1 Gbit/s, with 32 subcarriers, and quadrature amplitude modulation (16 QAM) is used to modulate the transmitter signal associated to the subcarriers, the carrier frequencies were obtained using the frequency multiplication explained previously (see section 4.1), RF carriers at 2 GHz and 15 GHz were used to carry the OFDM data. The generated signal travels along 40 km of SSMF, an FBG filter is used to remove the optical carrier so it can be reused for uplink data modulation with a bit rate of 1 Gbit/s travelling along 40 km of SSMF back to the CO. At the BS an FBG used in reflection centered at 193.1 THz with a bandwidth of 18 GHz is used to isolate the two second order sidebands generated at fo + 4 GHz and fo – 4 GHz, the reflected signal goes through a circulator and the signal is detected by a PIN photodiode. The transmitted spectrum, containing the two second order sidebands at fo + 30 GHz and fo – 30 GHz is also directly detected. After being detected the signals are mixed with LO at frequencies of 4x fm (respectively at 8 GHz and 60 GHz), in order to obtain the desired frequency quadruplicating, the resulting electrical signals are then filtered and received by OFDM signal analyzers in order to evaluate the signals EVM among other parameters. According to the spectral attribution defined by IEEE802.15 Working Group, UWB frequency bands belong to 3.1 – 10.6 GHz [IEEE 802.15, 2004], and Wireless Local Area Networks and Wireless Personal Area Networks applications might be allowed to be deployed also across the unlicensed frequency range of 57-64 GHz [IEEE 802.15.3c, 2007], hence the choice of frequency bands in the system presented in figure 4.16. The maximum permissible relative constellation error is set to a root mean square (RMS) EVM of 14.13% [ECMA-368, 2007].

System EVM variation for different laser powers for B2B and with 40 km of SSMF, is depicted in figure 4.17,

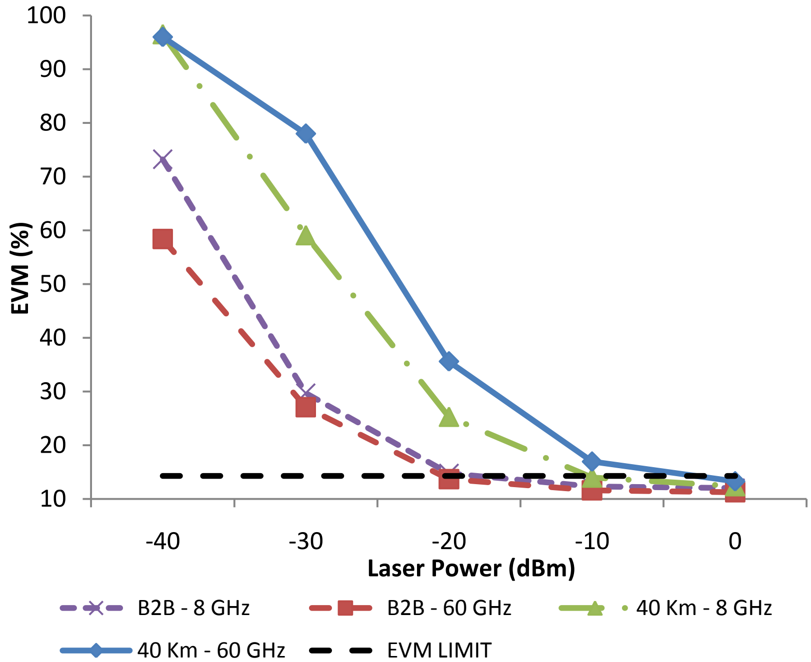


Figure 4.17 – EVM vs. Laser Power for B2B and 40 km of SSMF

Laser power was swept from -40 to 0 dBm in order to see system variation, optimal EVM values were achieved for 0 dBm. Next figure shows the variation in system performance for several fiber lengths,

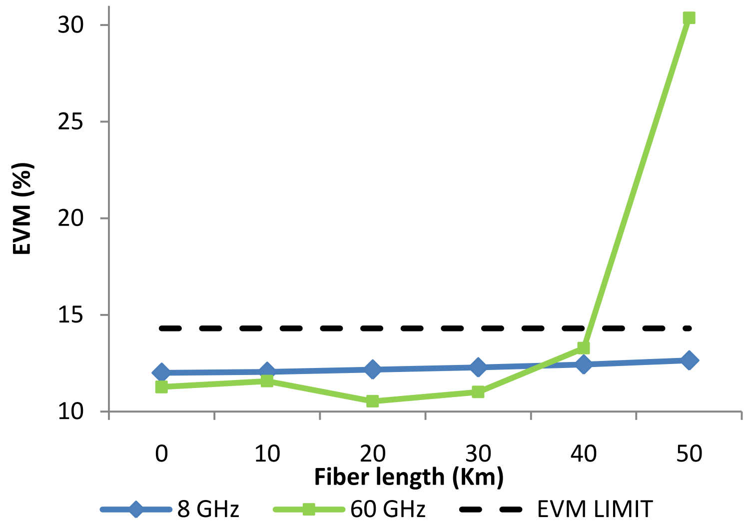


Figure 4.18 – EVM vs. fiber length

The signal at 8 GHz has approximately the same performance for all the tested distance, the limitation in distance is due to the 60 GHz signal, due to dispersion effects induced by the optical fiber. The EVM for 40 km of fiber was of 13.28% for the 60 GHz signal and 12, 4 % for the 8 GHz one, meeting the standards requirements.

4.3.2 Frequency Quadrupler for mm-wave carrier suppressed OFDM-UWB signals

The advantages of suppressing the carrier component in the modulation stage are well known from the signal processing aspect in communication systems, and were already documented in previous sections. It is also well known that transmission of the carrier is a waste of power since the information is carried by the sidebands. Furthermore, the suppression of the carrier leads to improve important characteristics of the fiber optic link such as dynamic range and noise figure.

In the presented simulation same type of modulation used previously (4.2.2) is applied, the impact of this type of modulation is studied in terms of system performance in OFDM

UWB transmission scenario and a comparison in terms of EVM is made between this and the previous scenario. Figure 4.19 presents system variation for different laser powers,

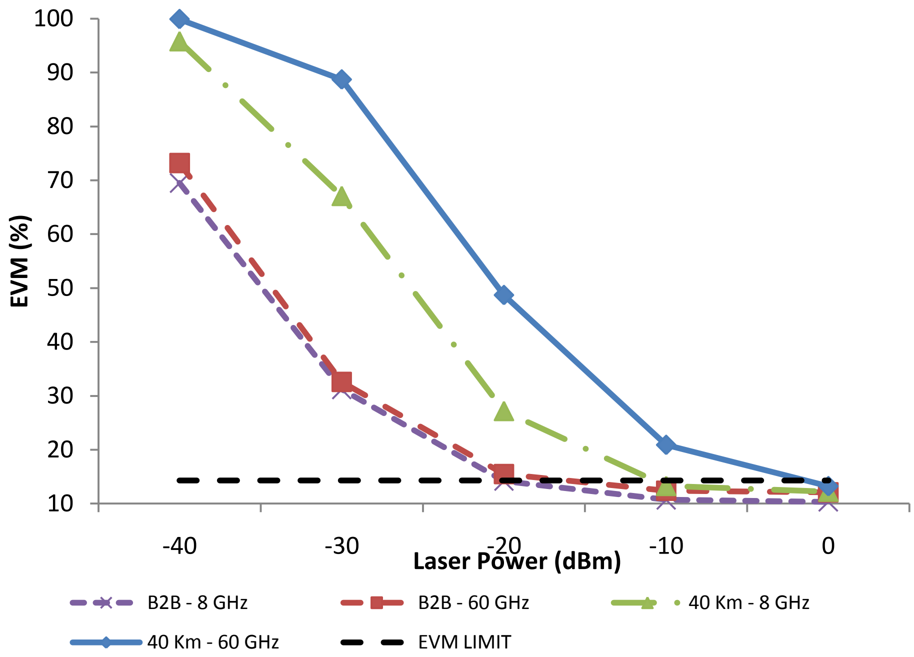


Figure 4.19 – EVM vs. Laser power (C.S CO)

Slightly better results than previously were obtained, although as in the previous situations the better EVM value was achieved for a laser power of 0 dBm, and for the 60 GHz signal the EVM is near threshold for 40 km of fiber.

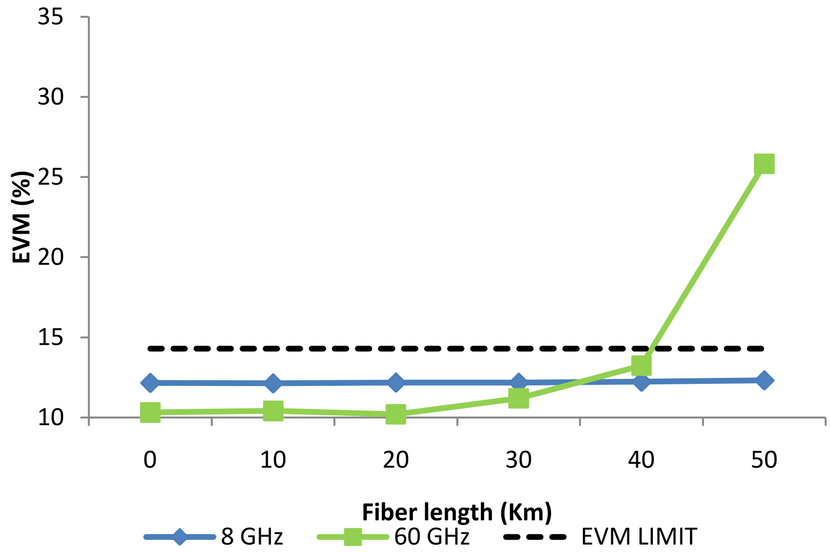


Figure 4.20 – EVM vs. Fiber length (C.S CO)

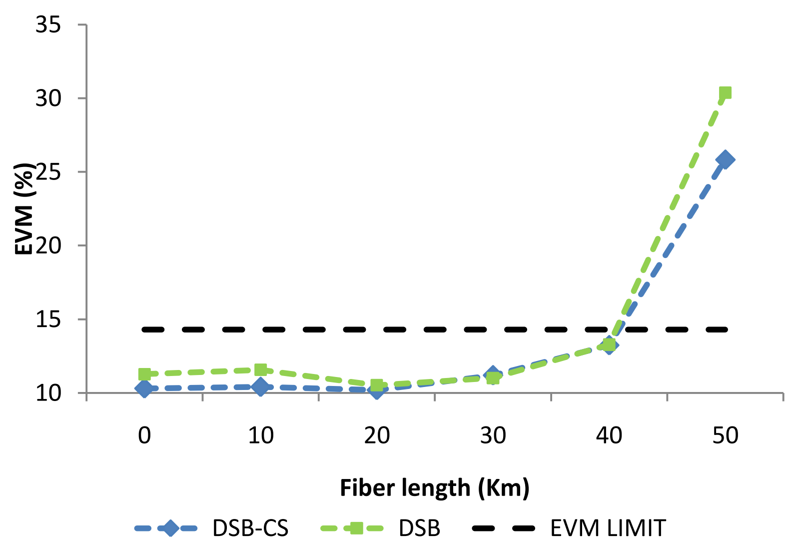


Figure 4.21 - Comparison between DSB and DSB-CS modulation for OFDM

Figure 4.20 shows the variation with fiber distance, and figure 4.21 shows a comparison between the two types of modulation (DSB and DSB-CS) for OFDM data transport. The difference between the two systems is not much, however the DSB-CS modulation has better performance has expected, mainly from 0 to 20 km, with an advantage of a lower cost to the system

4.4 Conclusions

The simplest fiber-radio links employ amplitude modulation (AM) of light at the transmitter and direct detection (DD) at receiver's photodetector. However, these systems are attractive for low-frequency applications and short distances only. At high carrier frequencies like the one tested in previous sections the required modulation devices become very costly. Furthermore, link lengths are severely limited (e.g. < 5 km for a 30 GHz carrier) by fiber disperse induced fading [Ng'oma, 2007]. A solution for higher frequencies systems and to achieve longer link lengths, is the use of alternative RoF techniques such as Remote Heterodyning (RHD), Single Side Band (SSB) transmission, advanced modulation formats (for example OFDM – Section 4.3). However a commitment of complexity and cost of the system must be taken into account.

In this chapter Frequency multiplication was validated using simulation software, and several setups were presented and discussed. The presented methods shows a low cost way of generating high frequencies signals, the state-of-the-art MZM has an upper-limit frequency response of about 40 GHz [Jiang, 2009], which demonstrates the benefit of employing frequency multiplication to generate frequencies above this value.

Chapter 5. Optical Generation and distribution of OFDM Ultra wideband Signals over Fiber

5.1 Introduction

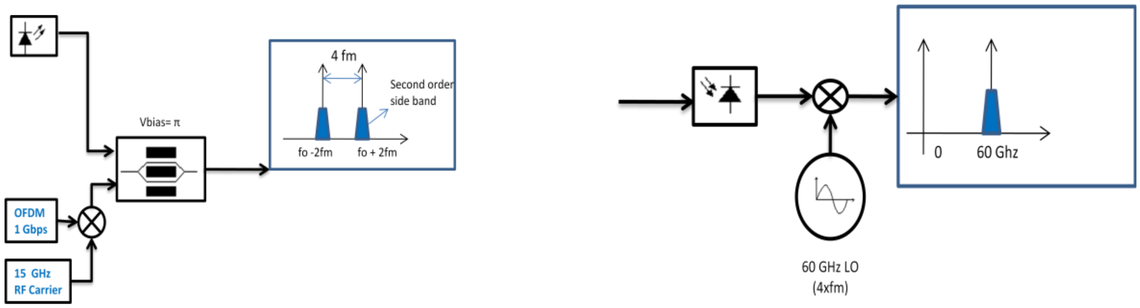
With the constant evolution of wireless based networks systems requirements, the emergence of new applications such as wireless multimedia, and increasing demand for wireless access networks in home, office and public environments, an increase in data rates is required. In order to ensure the higher data rates in future wireless systems, it is important to design systems with larger bandwidths, and increased spectral efficiency, maintaining or reducing associated costs. One way to satisfy the requirements mentioned above is the use of ultra-wideband communication (UWB) [Ran, 2009], which is a potential candidate for short-range multiple access wireless communication applications, including indoor static wireless local area networks, decentralized multiple access communication and secure military applications [Frenzel, 2008]. According to the spectral attribution defined by IEEE802.15 Working Group, UWB frequency bands belong to 3.1 – 10.6 GHz [IEEE 802.15.3a, 2004], and Wireless Local Area Networks and Wireless Personal Area Networks applications might be allowed to be deployed also across the unlicensed frequency range of 57-64 GHz [IEEE 802.15.3c, 2007]. The multiband (MB) UWB spectrum is split into a number of sub-bands, which allows the use of narrowband techniques within each sub-band. One particular technique associated with the UWB transmission, is the OFDM, that is used to transmit data in parallel, by using a large number of modulated carriers, with the subcarrier frequencies chosen in such a way that they are orthogonal over one OFDM symbol period [Couch, 2001]. MB UWB OFDM technology combines the advantages of spectrum efficiency, data modulation and OFDM. Additionally, wireless fiber communication networks operating at mm-wave frequencies have been considered for delivering broadband multimedia services to mobile terminals [Tatu, 2009]. When RoF is used for the distribution of mm-wave wireless signals, mm-waves can be generated optically. One solution is optical frequency multiplication [Lin, 2008] [Mohamed, 2008], using the non-linear response of a Mach-Zehnder modulator (MZM), driven by a RF signal, lowering the bandwidth requirements for the optical modulator and thus reducing costs.

The purpose of this work is to demonstrate the feasibility of a RoF based network, which combines all the features listed above, considering high data rates (500 Mbit/s, 1Gbit/s), and millimeter-wave frequencies in standard UWB bands, from 3.1 to 10.6 GHz and from 57 to 64 GHz, respectively 8 GHz and 60 GHz. The proposed architecture allows the simultaneous transmission of unicast and multicast contents, using three optical channels for each of them. In this work, we study the performance of OFDM signals, UWB compatible, in WDM-RoF systems with potential application in the access network.

5.2 – System description

To generate the 500 Mbit/s and 1 Gbit/s OFDM-UWB signals with these UWB compatible mm-wave carriers' frequencies, we have used a MZM in non-linear regime (to allow frequency duplication) and RF carriers at 2 GHz and 15 GHz, respectively. The referred optical frequency duplication was achieved using a Mach-Zehnder modulator (MZM), dc-biased at the peak output power to suppress the odd-order sidebands [Rujian, 2009] [He, 2009]. Doing so, two second-order optical sidebands are generated with a frequency spacing of four times the driving radio frequency, and thus frequency quadrupling is achieved (see Figure 5.1). We considered carrier suppressed/unsuppressed

DSB modulation, respectively for multicast and unicast transmission, the later one allowing optical carrier reutilization for uplink traffic. Signal routing is performed using a cyclic AWG directing each wavelength to the destination users.



(i) (ii)

Figure 5.1 (i) Frequency duplication at MZM (RF carrier with frequency fm=15GHz), (ii) Frequency quadrupling at the receiver using a LO at 4×fm=60 GHz.

As referred previously our architecture uses carrier-suppressed modulation for down-link broadcasting. The use of CS modulation is advantageous, to avoid reaching the power level for nonlinearly induced distortion associated to propagation, and also because no narrow filter is needed to remove the optical carrier at the receiver, leading to higher tolerance to frequency variations and increasing transparency. The configuration used for the optical carrier suppressed modulator is described in figure 5.2 (only one channel depicted for simplicity).

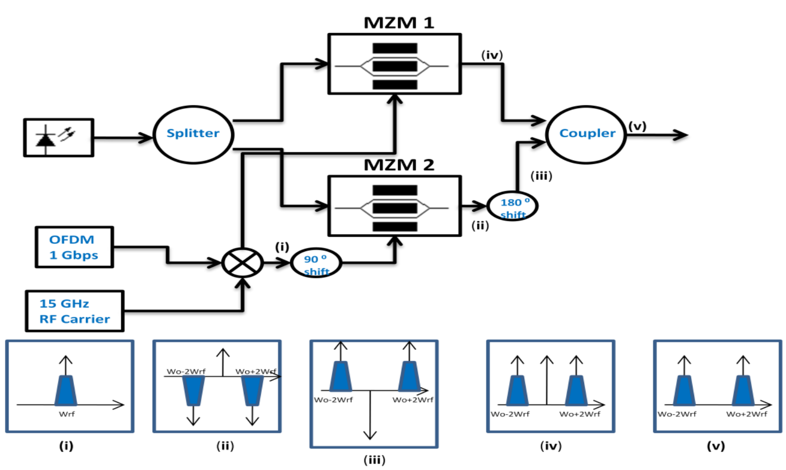
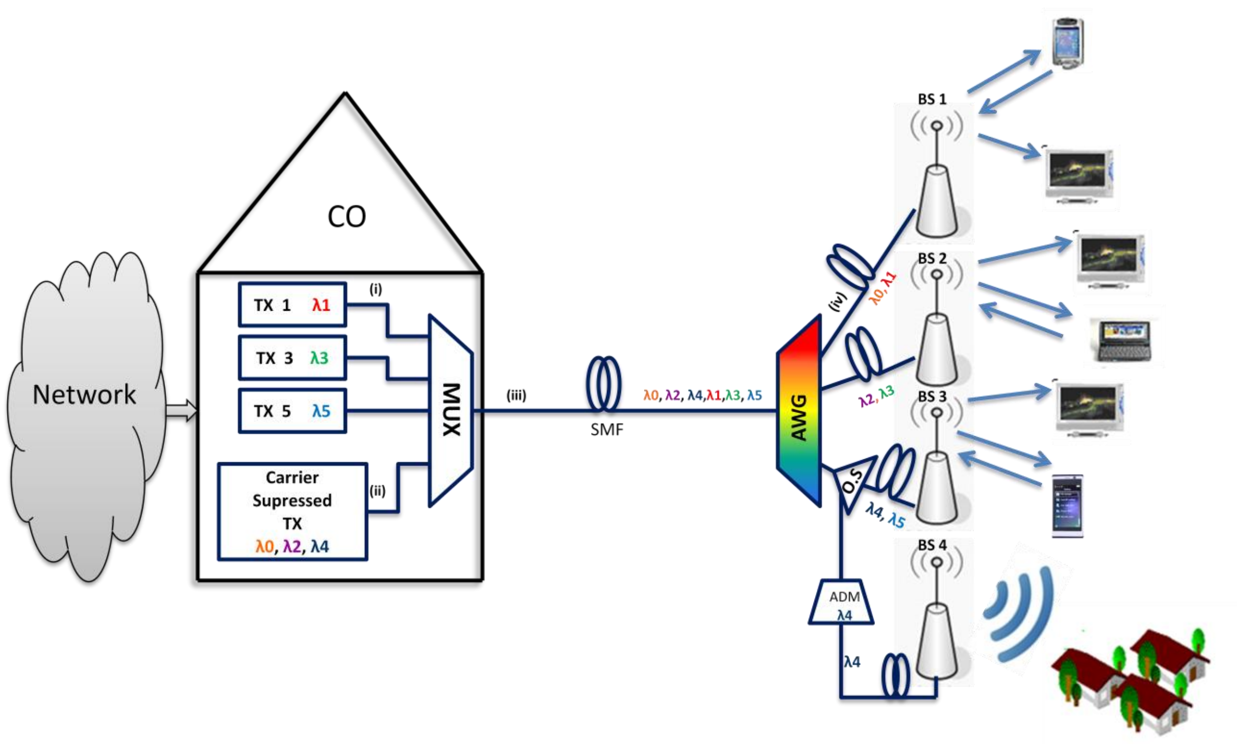


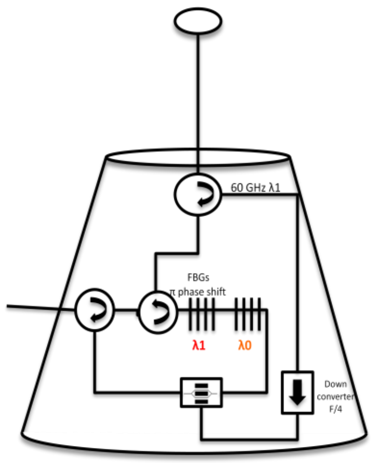
Figure 5.2 – Optical carrier suppressed modulator

Figure 5.2 (ii) shows the configuration of the C.S modulator used, the associated concepts are the same explained in section 4.2.2.

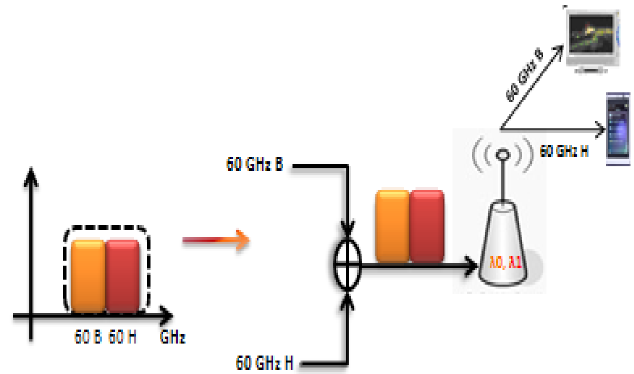
The proposed system (Figure 5.3 (a)) consists of one CO (Central Office) with four optical transmitters, whose signals are then multiplexed to generate the WDM signal, a standard SMF, a cyclic AWG for signal routing and four BS (Base Stations) at the receiving end (see Figure II.3 (b) for details on the BS structure). At the CO, a carrier suppressed transmitter (Tx- figure II.3 (a)) is responsible for sending three channels λ0, λ2, λ4 with a channel spacing of 100 GHz respectively at 193.1 THz, 193.2 THz and 193.3 THz. Each wavelength transports two frequency bands (carrier frequencies of 4 GHz and 30 GHz, which are generated by frequency doubling as referred), with the same OFDM data, intended for broadcasting.



(a)



(b)



(c)

Figure 5.3 (a) – System architecture, (b) – BS 1 scheme, (c) Signal processing at the receiver

Tx1, Tx2 and Tx3 transmit three optical channels λ1, λ3, and λ5, again with a channel spacing of 100 GHz, respectively at 194.1 GHz, 194.2 GHz and 194.3 GHz, and, like in the previous case, each wavelength carries two bands (with carriers of 4GHz and 30 GHz), with OFDM data. In this situation, for unicast transmission, each wavelength transports different data. Signals from transmitters are multiplexed using a 4x1 MUX (Figure 5.3 (a)), then the WDM signal is propagated along standard SMF over distances up to 15 km. Routing is performed by an AWG with a free spectral range of 1 THz and then each output port is connected to a BS, as illustrated in Figure 5.3 (a). Considering the depicted topology, each BS receives broadcast and unicast signals. Another architecture approach would be possible, using an optical splitter instead of the cyclic AWG, but in this case, all the wavelengths would reach the BSs, significantly increasing the need for filtering and hence the complexity and costs of the network. Another reason for choosing an AWG routing method is that the typical insertion loss of the AWG is considerably below the correspondent to a 1:4 optical splitter (approximately 9 dB of loss). Using an AWG, additionally, improves upgradability, for serving more BSs if necessary, without increasing the losses associated.

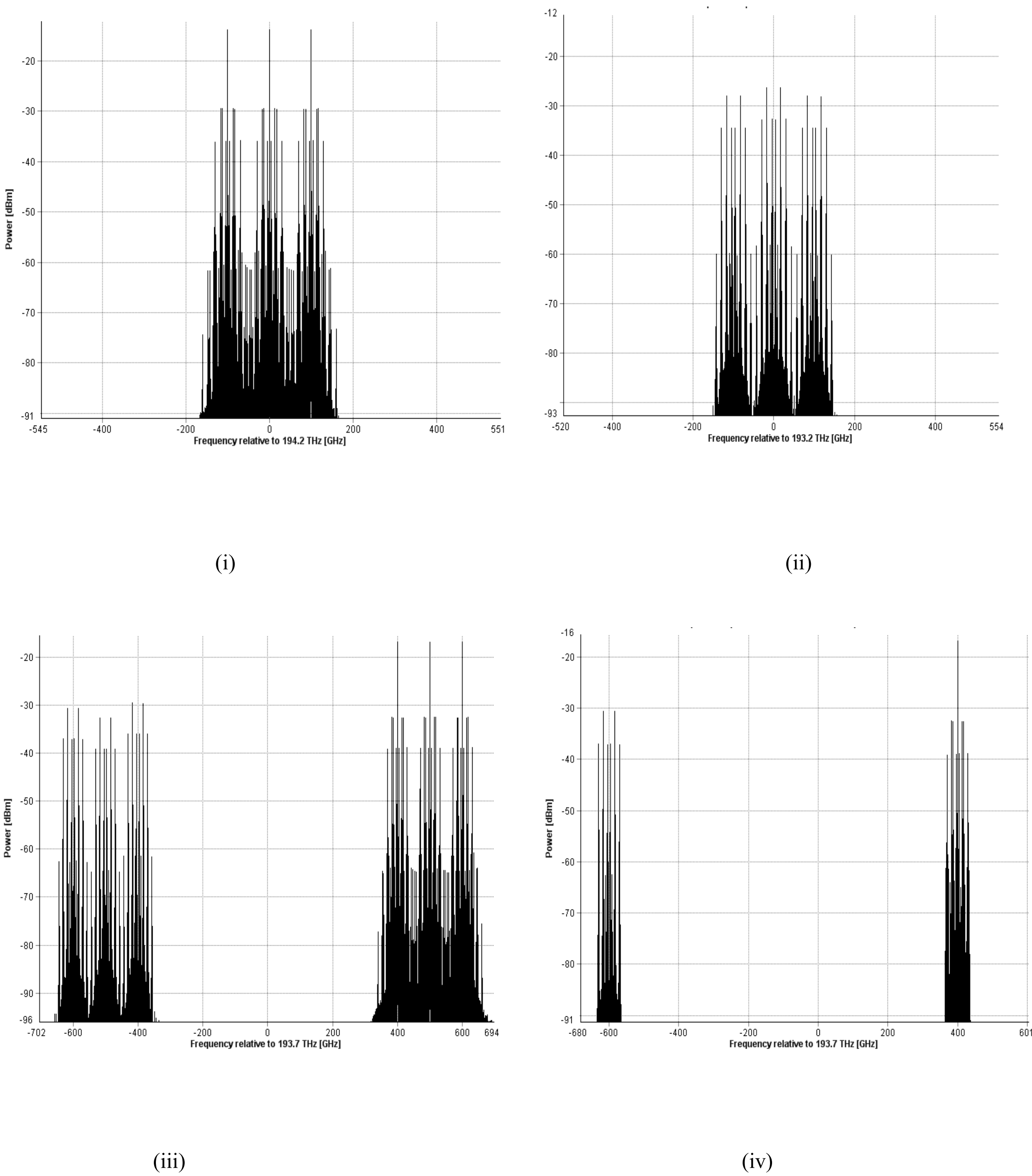


Figure 5.4 Optical spectra (i) Tx1, Tx3, Tx5 (ii) CS Tx (iii) MUX output (iv) AWG output 1.

Figure 5.4 shows the optical spectra at different points of the system. Figure 5.4 (i) represents the optical spectrum associated to unicast signal, and Figure 5.4 (ii) shows the optical spectrum at the output of the CS modulator. It is possible to observe the absence of the optical carriers in this later case. In Figure 5.4 (iii) the WDM optical spectrum is illustrated, and Figure 5.4 (iv) represents the optical spectrum of the signal reaching BS 1 (channels λ0 and λ1).

The BS structure is illustrated for the BS 1 case, in figure II.3 (b). After being detected, the signal passes through two FBGs. One with a π phase shift, used in transmission, centered at λ1, so that the entire spectrum of the signal is reflected, except the optical carrier λ1, which is routed to an MZM, and reused for uplink data modulation. Another FBG, used in reflection, centered at λ0, so that the entire CS incoming spectrum is reflected and sent to the antenna through the circulator. After being photo detected, the resulting electrical signal is mixed with a LO at four times the RF carrier frequencies at the transmitter (2 GHz and 15 GHz as referred), resulting in 8 GHz and 60 GHz signals. The uplink UWB signal is down converted, and then modulates the reused optical carrier. In order to process both broadcast and unicast signals, using only one BS, and thus make the system more efficient, different sub-bands were used for the signals as illustrated in fig 5.3 (c).

BS 4 illustrates another possibility for broadcast transmission (figure 5.3 (a)). In fact, using and ADM (add-drop multiplexer) and dropping a broadcast channel (for example λ4), enables additional coverage with a simpler BS, increasing the upgrading potential of the system. Our topology (Figure 5. 3 (a)) also has the advantage of allowing turning on and off users independently. For example, if for some reason BS 1 wants to stop receiving the contents from the Tx provider (broadcast), turning off λ0 laser is enough, and still the other users continue to receive the signal from the Tx, transmitted in λ2 and λ4, so the network management is extremely simple and effective.

5.3- Simulation results and discussion

In order to validate the presented system some tests were made, using the commercial software VPI Transmission Maker and the network topology explained in section II. The performance of the system is evaluated in terms of error vector magnitude (EVM) [McKinley, 2004].To accomplish an efficient network architecture enabling optical generation and distribution of OFDM UWB signals over fiber, several systems were considered. A reference system was analised, considering the same architecture presented in figure 6.3 (a), but using optical single side band (SSB) modulation, with a single RF carrier at 60 GHz from the optical carrier. A performance comparison to the DSB (two RF carriers at ±30 GHz from the optical carrier) and DSB-CS (same as DSB but suppressing carrier) modulations described in section II was made, and the results are presented in Figure 6.5. The transmitted mean optical power for all Lasers was 0 dBm and the bit rate 1 Gbps.

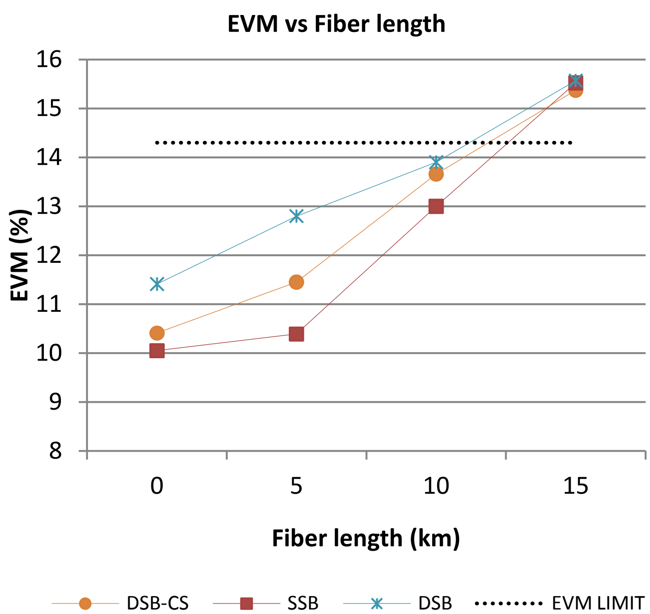


Figure 5.5 – EVM vs fiber length for DSB, CS-DSB and SSB system.

As it is possible to observe in Figure 5.5, the SSB system without frequency multiplication presents the best performance, however slightly better than DSB and CS-DSB cases referred, just 1% - 2% lower EVM, but still, the use of the presented configuration with DSB (CS or not) and frequency multiplication is advantageous, since it allows the use of external modulators with ¼ of the bandwidth and greatly reduces the bandwidth requirements of the components composing the system, thereby reducing system costs with imperceptibly slight decrease of performance. For all the modulations considered, a fiber length of approximately 10-12 km can be achieved.

For all the tests, the distance between the routing part (AWG) and BS was 500 m, varying the distance from the CO to that point. For the simulations, an OFDM signal with 32 subcarriers was considered, and quadrature amplitude modulation (16 QAM) was used to modulate the transmitter signal associated to the subcarriers. As defined in chapter 4, for this type of signals, the maximum permissible relative constellation error is set to a root mean square (RMS) EVM of 14.13% [ECMA-368, 2007]. The limit in transmission distance is due to the optical fiber dispersive behavior associated with the transmission of RF signals over fiber, and non linearities, mainly FWM. In fact, with an increase in channel spacing the EVM penalty decreases. In order to test the impact of channel spacing in EVM penalty only two transmitters were used, one with constant λ= 193.1 THz and another with varying wavelength, from 193.2 to 193.6 THz. The signals were multiplexed the same way as made in the original setup, detected, and the EVM associated with the data received from the first transmitter was evaluated. For a 100 GHz spacing between channels the EVM obtained was 12.5%, while for a spacing of 400 GHz it decreases to 9.5%. However, spacing between adjacent channels of 100 GHz was used, in order to ensure low bandwidth requirements for the network.

In the following presented results, only one of the channels transmitted in each band (multicast or unicast) was studied as the other ones presented the same behavior. A slightly difference in performance can be observe between the signals with DSB-SC modulation and DSB ones, so for this reason we present results for one channel in each band, $\lambda 0$ for the CS modulator and $\lambda 3$ for the Tx3 modulator (see figure 5.3 (a)). Figure 5.6 shows the EVM variation for different laser powers, for 15 km of fiber and a bit rate of 1 Gbit/s. It is possible to conclude that with the increase in power, the EVM decreases sharply from -30 dBm to -10dBm, and the optimal power is 0 dBm. Then, EVM stabilizes until 0 dBm. Further increasing the power leads to EVM increase due to the introduction of too much power in the fiber that enhances the effect of nonlinearities.

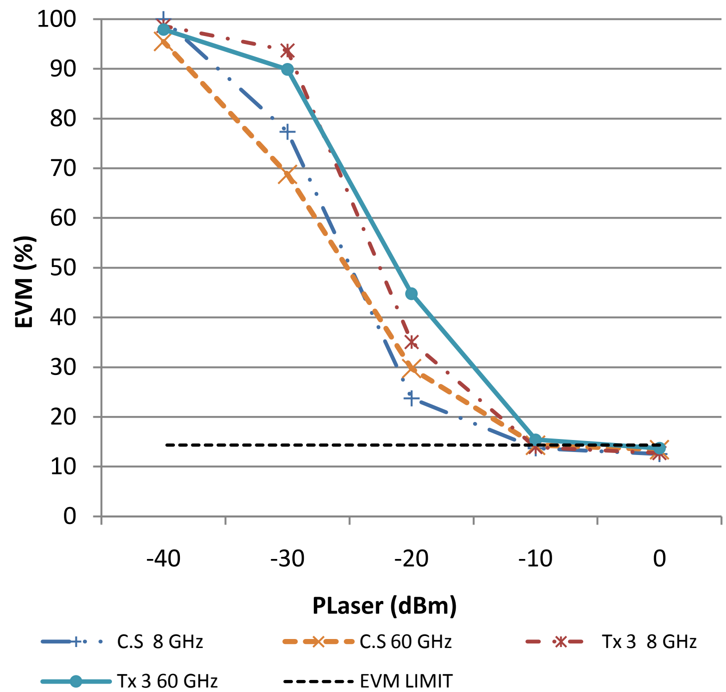
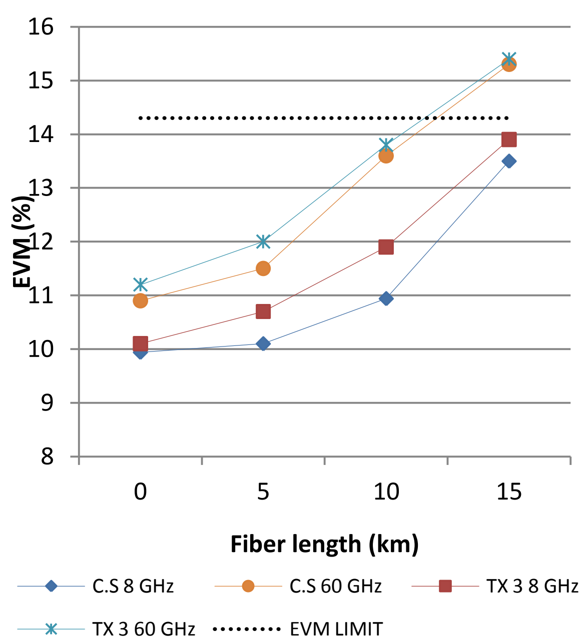
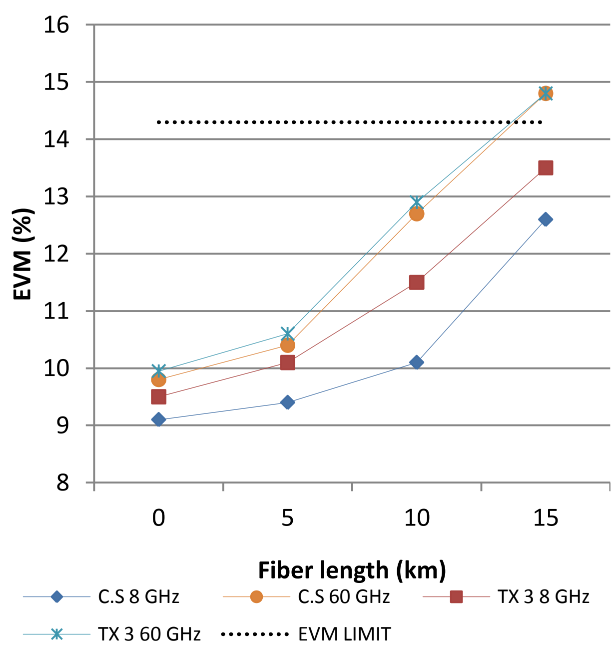


Figure 5.6 - EVM vs Laser power for 10 km of fiber and 1 Gbps.



(i)



(ii)

Figure 5.7 EVM vs fiber length for different bit rates (i) 1 Gbit/s (ii) 500 Mbit/s

To evaluate how the system reacts to different bit rates, the EVM vs fiber length was also measured for 500 Mbit/s and 1 Gbit/s data (results in Figure 5.7). The difference between both results was not significant, around 1% better for the lower bit rate, but this demonstrates that with an increase in bit rate the system keeps roughly the same performance. The results for the band with 8 GHz carrier were better than for the 60 GHz case, as expected, due to impact of the RF response of the fiber, associated to dispersion.

5.4 - Conclusions

Aiming low cost and simplicity, an architecture using RoF-WDM, which allows transmission of signals using OFDM technique, UWB compatible, was presented. The generation of the OFDM-UWB signals with the desired mm-wave carriers' frequencies was made using an optical frequency-quadrupling technique, thus with lower bandwidth requirements for the optical modulator. Two types of modulation were used, DSB for up-/down-link unicast transmission and CS-DSB for downlink multicast, the later one providing higher transparency and robustness to non-linear phenomena. Successful transmission was made up to 12 km over standard SMF, with an EVM below the established in the standard (14.13%).

Chapter 6. Conclusions and proposed work

6.1 Conclusions

This thesis has investigated a concept of Radio over Fiber generation and transmission over optical links, using several techniques and recurring to optical frequency multiplication.

The presented work is composed of six chapters were the main discussed thematic is ROF properties, and RF signals behavior when associated with optical techniques and components. Chapter one presents an overall idea of the concepts that ROF involves and also the main advantages of the use of this type of technology. In chapter two the main constituent components of a typical optical link involving generation, transmission and detection of radio signals over optical fiber, are presented and discussed and the major limitations associated, as well as ways to overcome them are presented. Chapter three consists of several experimental tests in order to evaluate and identify some of the impairments discussed in the previous chapter, as seen some effects like laser clipping, modulation AM and FM efficiency, SOA gain saturation among other parameters can have an important impact in systems performance. In chapter 4 commercially available software VPI Transmission Maker was used to perform several simulations involving optical frequency multiplication, for millimeter and microwave generation and transmission. It has been shown that OFM can be used to realize radio-over-fiber bidirectional transmission between a centralized headend and radio access units. Two types of modulations were tested amplitude modulation of RF signals over an optical carrier, and advanced modulation technique – OFDM, using DSB or DSB-CS modulation. As seen in the simulations the carrier suppressing technique is very handful in systems, the amount of optical power that travels along optical fiber is substantially reduced because of the absence of the optical carrier, due to this fact, the impact of optical fiber non linear effects on the signal are reduced improving system performance and transmission distance. Amplitude modulation is proved to be one of the simplest forms of modulation, providing simplified low costs systems, however the generated signals are more susceptible to fiber dispersive and fading effect limiting transmission distance (around 4-7 km for bit rates up to 20 Gbit/s using 40 GHz RF carrier). Simple systems were used in order to validate the concepts of frequency multiplication using amplitude modulation, nevertheless these systems were capable of handling high data rates up to 7 km (20 Gbit/s). As tested in the simulation a solution to increase the distance travelled by the signal was the use of advanced modulation formats such as OFDM, increasing spectral efficiency of the generated signal. The presented systems confirmed the possibility of optical frequency multiplication with OFDM modulation format, and were able to generated high frequency UWB RF signals (60 GHz) and deliver them to BSs situated at approximately 40 km of the CO, respecting standards requirements for EVM values. Finally chapter 5 presented a novel system involving the system architectures presented in chapter 4, using RoF-WDM multi-carrier multiplexed signals, which allows transmission of signals using OFDM technique with frequency multiplication, UWB compatible. OFDM-UWB signals with the desired mm-wave carriers' frequencies were generated using an optical frequency-quadrupling technique, thus with lower bandwidth requirements for the optical modulator. Two types of modulation were used, DSB for up-/down-link unicast transmission and CS-DSB for downlink multicast, the later one providing higher transparency and robustness to non-linear phenomena. Successful transmission was made up to 12 km over standard SMF, with an EVM below the established in the standard (14.13%). This network architecture is inspired in future PON networks concepts like WDM-PON networks, being capable of delivering high data rates to final users employing broadcast and unicast transmission, and having routing functions implemented in the physical layer, an AWG is responsible of redirecting the corresponding wavelengths to the required BSs, and users connection and disconnection can be individually achieved at the COs, by a simple laser monitoring. As a term of conclusion this work permitted to verify that as expected by consolidating the signal processing at the centralized headend, the remote radio access units are significantly simplified. Thus optical frequency multiplication can help reduce system costs in next-generation dense high frequency broadband wireless systems, where numerous radio access units need to be deployed.

6.2 Proposed work

The extensive experimental and simulation work covered in this thesis was focused on the remote delivery of pure high-frequency microwave and millimeter wave signals to achieve significantly simplified BSs. However with the constant increase in network requirements and capacities, more advanced detection techniques can be required, whereas direct detection is a cost-effective method, the sensitivity of coherent OFDM is superior and enhances system performances at the cost of more complexity. The possibility of matching coherent detection techniques, optical frequency multiplication and OFDM modulation format can be a challenging work to test. The OFDM subcarriers used in the simulation setups were modulated using quadrature amplitude modulation (16 QAM), an increase to 64,128 and 256 QAM modulations and increased number of subcarriers employed can also be a tempting work in order to increase signal spectral efficiency, and hence the robustness of the systems.

References

[Bhardwaj, 2010] A. Bhardwaj, S. Ristic, L.A. Johansson, C. Althouse and L.A. Coldren,"Direct modulation bandwidth enhancement of strongly injection-locked SG-DBR laser", ELECTRONICS LETTERS 4th March 2010 Vol. 46 No. 5 (2010);

[Caiqin, 2006] Caiqin Wu,Xiupu Zhang, "Impact of Nonlinear Distortion in Radio Over Fiber Systems With Single-Sideband and Tandem Single-Sideband Subcarrier Modulations", JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 24, NO. 5, MAY (2006);

[Couch, 2001] L. W. Couch, II, "Digital and Analog Communication Systems." Upper Saddle River, NJ: Prentice-Hall, (2001);

[ECMA-368, 2007] ECMA-368 International Standard: "High rate ultra wideband PHY and MAC Standard", (2007);

[ETSI, 1995] – ETSI, "Mobile Station-Base Station Compatibility Standard for Wideband Spread Spectrum Cellular Systems", (1995);

[ETSI, 2008] – ETSI, "Universal Mobile Telecommunications System (UMTS); UTRA repeater radio transmission and reception", 3GPP TS 25.106 version 7.2.0 Release 7, (2008);

[fiber-optics,2010] http://www.fiber-optics.info/articles (2010);

[Francisca Martínez, 2007] "Transmission of IEEE802.16d WiMAX signals over radio-over-fibre IMDD links", (2007);

[Frenkel, 1998] - M. Y. Frenkel and R. D. Esman, "Optical single-sideband suppressed-carrier modulator for wide-band signal processing," J. Lightwave Technol., 16, pp. 859-863, May 1998.

[Frenzel, 2008] Louis E. Frenzel, "UWB Applications: Something For Everyone", Electronic Design, vol 33, (2008);

[Gliese, 1997] Graham H. Smith, Dalma Novak, and Zaheer Ahmed, "Overcoming Chromatic Dispersion Effects in Fiber-Wireless Systems Incorporating External Modulators", IEEE transactions on microwave theory and techniques, vol.45, no.8,august (1997);

[Goff, 2002] David R. Goff; Kimberly S. Hansen , "Fiber Optic Reference Guide: A Practical Guide to Communications Technology", Focal Pr, (2002);

[Hai-Han Lu, 2005] Hai-Han Lu, Wen-Shing Tsai, Hsiang-Chun Peng, Yu-Jie Ji, "A Comparison between Optical SSB Transmitter/Filter in a Full-Duplex Radio-on-Fiber Transport System", IEEE COMMUNICATIONS LETTERS, VOL. 9, NO. 7, JULY (2005);

[He, 2009] J. He, L. Chen, Z. Dong, S. Wen and J. Yu,"Full-duplex radio-over-fiber system with photonics frequency quadruples for optical millimeter-wave generation", Optical FiberTechnology, Volume 15, Issue 3, June 2009, Pages 290-295 (2009);

[Hilt, 2002]. A. Hilt, T. Berceli, I. Frigyes, E. Udvary, and T. Marozsak, “Fiber dispersion compensation techniques in optical/wireless systems”, 14th IEEE International Conference on Microwaves, Radar and Wireless Communications, (2002);

[IEEE 802.15.3a, 2004] Multi-band OFDM physical layer proposal for IEEE 802.15 taskgroup3a”, IEEE802.15 Working Group for WPAN, March 2004, (2004);

[IEEE 802.11, 2007] IEEE 802.11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, IEEE - SA, (2007);

[IEEE 802.15.3c, 2007] “Merged proposal: new PHY layer and enhancement of MAC for mm-wave system proposal,” IEEE 802.15.3c Working Group for WPAN, Nov.2007, (2007);

[Interscience, 2010] www.interscience.wiley.com;

[Jansen, 2007] S. L. Jansen, I. Morita, N. Takeda, H. Tanaka, “20-Gb/s OFDM transmission over 4,160-km SSMF enabled by RF-pilot tone phase noise compensation," OFC 2007,PDP 15, (2007);

[Jansen, 2008] S. L. Jansen, I. Morita, T. C. W. Schenk, N. Takeda, and H. Tanaka, “Coherent optical 25.8-Gb/s OFDM transmission over 4160-km SSMF," J. Lightwave Technol., vol. 26, no. 1, pp.6-15, Jan. 2008.

[Jianxin Ma, 2009] – Jianxin Ma, ” Transmission of a 40 GHz optical millimeter wave generated by quadrupling a 10 GHz local oscillator via a Mach–Zehnder modulator”, J. Opt. A: Pure Appl. Opt. 11 (2009);

[Li, 2010],Li J, Ning T, Pei L, Qi C, Hu X, Zhou Q,” Photonic frequency-quadrupling scheme for millimeter-wave generation by employing feed-forward modulation technique.”, Opt Express. 2010 Feb 1, (2010);

[Lin, 2008] Chun-Ting Lin, Po Tsung Shih,” Generation of Carrier Suppressed Optical mm-wave Signals using Frequency Quadrupling and no Optical Filtering”, OFC/NFOEC (2008);

[Lowery, 2007] A. J. Lowery, L. B. Du, and J. Armstrong, \Performance of optical OFDM in ultralong-haul WDM lightwave systems," J. Lightwave Technol., vol. 25, no. 1, pp.131-138, Jan. (2007);

[Ma, 2007]. J. Ma, J. Yu, C. Yu, X. Xin, J. Zeng, and L. Chen, “Fiber dispersion influence on transmission of the optical millimeter-waves generated using LN-MZM intensity modulation”, J Ligthwave Technol 25 (2007), 3244–3256.

[McKinley, 2004] Michael D. McKinley, Kate A. Remley, Maciej Myslinski, J. Stevenson Kenney, Dominique Schreurs, Bart Nauwelaers, “EVM Calculation for Broadband Modulated Signals”, 64th ARFTG conf, Dig. , Orlando, FL, pp. 45-52, Dec. (2004);

[Mohamed, 2008] M. Mohamed, X. Zhang, B. Hraimel, and K. Wu, “Analysis of frequency quadrupling using a single Mach–Zehnder modulator for millimeter-wave generation and distribution over fiber systems”, *Opt. Express*, vol. 16, no. 14, pp. 10786–10802, July (2008);

[Opatic, 2007]D.Opatic,"Radio over Fiber Technology for Wireless Access", (2007);

[Pham, 2008]Thang T. Pham, Hyun-Seung Kim, Yong-Yuk Won and Sang-Kook Han,Bidirectional 1.25Gbps WDM RoF Wired Wireless Optical Transmission using Multiple SSB Carriers in FP LD by Multiple Mode Injection Locking, ECOC 2008, 21-25 September (2008);

[Park, 2005]Sang-hiu Park,Chromatic Dispersion Tolerance of the SSB-Modulated Signals, Journal of the Optical Society of Korea, Vol. 9, Issue 1, pp. 13-15 (2005);

[Pospiech, 2004], Matthias Pospiech, Sha Liu,"Laser Diodes an Introduction",University of Hannover, Germany (2004);

[Prasad, 2004] R. Prasad, OFDM for Wireless Communications Systems, Artech House Publication, (2004);

[Proakis, 2005] J.G. Proakis and M. Salehi, Essentials of Communications Systems Engineering, Chapter 11, Prentice Hall, (2005);

[Qi, 2009] G. Qi, J. P. Yao, J. Seregelyi, C. Bélisle, and S. Paquet, “Generation and distribution of a wide-band continuously tunable millimeter-wave signal with an optical external modulation technique,” IEEE Trans. Microw.Theory Tech., vol. 53, no. 10, pp. 3090–3097, Oct. (2009);

[Rahman, 2009] Mohammad Shaifur Rahman, Jung Hyun Lee, Youngil Park, and Ki-Doo Kim, "Radio over Fiber as a Cost Effective Technology for Transmission of WiMAX Signals", World Academy of Science, Engineering and Technology 56 (2009);

[Ran, 2009] M. Ran, Y. Ben Ezra, and B. Lembrikov, “Ultra-wideband radio-over-optical fibre, in Short-Range Wireless Communications: Emerging Technologies and Applications”, R. Kraemer and M. Katz, Eds. New York: Wiley, 2009, ch. 24, pp. 271–327, (2009);

[Rujian, 2009] Rujian LIN, Meiwei ZHU, Zheyun ZHOU, Haoshuo CHEN, Jiajun YE, “New progress of mm-wave radio-over-fiber system based on OFM”, Front. Optoelectron. China (2009);

[Tatu, 2009] S. O. Tatu, E. Moldovan, and S. Affes ,“Low-Cost Transceiver Architectures for 60 GHz Ultra Wideband WLANs”, International Journal of Digital Multimedia Broadcasting Volume (2009);

[TSANG, 2009]TSANG Hon Ki, LI Chao ,”Optical mm-Wave Signal Generation by Frequency Quadrupling Using an Optical Modulator and a Silicon Microresonator Filter”, IEEE Photonics Technology Letters, vol.21, no.4, 2009, pp.209-211, (2009);

[Thyagarajan, 2003] K. Thyagarajan,"Linear and Nonlinear Propagation Effects in Optical Fibers", Springer Berlin / Heidelberg, Volume 613/2003, (2003);

[Viščor Ivo, 2001] Viščor Ivo, Halámek Josef, “Laser Phase Noise Measurement”, Proceedings of the Radioelektronika 2001, Brno 2001, pp. 131 – 134 (2001);

[Watts, 2004] P.M.Watts, V.Mikhailov, M.Glick, P.Bayvel, R.I.Killey, “Single Sideband Optical Signal Generation and Chromatic Dispersion Compensation using Digital Filters”, Electronics Letters, 22 July 2004,Vol. 40. No.15, (2004);

[Wen-Jr Jiang, 2009] Wen-Jr Jiang, Chun-Ting Lin, Han-Sheng Huang, Po-Tsung Shih,Jason(Jyehong) Chen, and Sien Chi, “60-GHz Photonic Vector Signal Generation Employing Frequency Quadrupling Scheme for Radio-over-Fiber Link”, OSA/OFC/NFOEC 2009, (2009);

[Xavier Fernando, 2009]Xavier Fernando, "Radio over Fiber for Wireless Access Motivation An Optical Technique", Presentation for Ryerson Communications Lab, (2009);

[Yu, 2006] J. Yu, Z. Jia, L. Yi, Y. Su, G.-K. Chang, and T. Wang, “Optical millimeter-wave generation or up-conversion using external modulators”, IEEE Photon. Technol. Lett., vol. 18, no. 1, pp. 265–267, Jan. (2006);