QUADRATURE AMPLITUDE MODULATED (QAM) MICROWAVE SIGNAL TRANSMISSION OVER A RADIO-OVER-FIBRE LINK USING SEMICONDUCTOR OPTICAL AMPLIFIERS

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Submitted In Fulfillment Of The Requirements For The

Master Degree Of Telecommunication Enginneering

At

University of Limerick

Limerick, Ireland

September 2008

Resumen del Proyecto

Descripción General y Objetivos

El presente proyecto de investigación ha sido llevado a cabo en el laboratorio del Grupo de Comunicaciones Ópticas de la *University of Limerick* durante el periodo comprendido entre febrero y julio de 2008. En él se describe y estudia la calidad del montaje de un sistema completo de transmisión de señales moduladas en rango de radiofrecuencia sobre un esquema de comunicaciones ópticas (transmisor óptico, fibra óptica, amplificador óptico semiconductor y receptor o convertidor óptico-eléctrico), siendo el propósito principal analizar los resultados experimentales obtenidos y comparar con los resultados teóricos esperados en términos de unas magnitudes específicas de error.

La realización del experimento incluye tres partes bien diferenciadas. En primer lugar, un aprendizaje e investigación para establecer la base teórica sobre el tipo de sistemas requeridos y los formatos de modulación asociados con respecto al uso de SOAs; en segundo lugar, una familiarización con los complejos equipos de testeo y el complicado software empleado para la generación y análisis de la señal; y en último lugar, el trabajo experimental que requirió el montaje del sistema completo y análisis de variables y medidas para establecer conclusiones finales.

Motivación

Los sistemas de transmisión de señales de radio sobre fibra, que combinan dispositivos de radiofrecuencia con enlaces de fibra óptica, han motivado un gran interés en multitud de aplicaciones en las redes de telecomunicación actuales y la última década. Una de las principales razones por la que estos sistemas resultan tan atractivos hoy día se debe al resultado de las investigaciones en recientes estudios experimentales, que demuestran que la fusión entre estos dos tipos de tecnología tan distintos permite aprovechar mejor las capacidades que ofrecen ambas, además de proveer beneficios adicionales en una gran variedad de aplicaciones, tales como antenas remotas y estaciones de satélite o aplicaciones inalámbricas. Entre otras propiedades que más atención han suscitado estos sistemas destaca su potencial reducción de costos operacionales, un factor de vital importancia que requieren los sistemas y aplicaciones actuales.

En esencia, los sistemas de radio sobre fibra presentan un gran interés tecnológico por la viabilidad de transmitir y/o distribuir la información a través de canales de fibra óptica de media y larga distancia, con las ventajas asociadas a este medio de transmisión.

En primer lugar, las bajas pérdidas que posee la fibra en tercera ventana (inferiores a 0,25 dB/km para una longitud de onda de 1550 nm) unido a la presencia de amplificadores ópticos (por ejemplo, los Amplificadores Ópticos de Semiconductor utilizados) permite alcanzar grandes distancias. Asimismo, la tecnología de fibra óptica ofrece otras ventajas de rendimiento sobre soportes más tradicionales como el cable coaxial, ya que proporciona inmunidad frente a las interferencias, alta frecuencia de trabajo y un elevado ancho de banda de transmisión, únicamente limitado por la dispersión cromática.

Breve descripción del experimento

Como se menciona anteriormente, en esta memoria se estudia de forma experimental la calidad de un sistema de transmisión de microondas a través de un enlace de fibra que incluye amplificadores ópticos semiconductores (SOA), en términos de la magnitud de vector de error (EVM) y tasa de error de bit (BER). Resultados experimentales revelan que una señal 16-QAM viajando a una tasa de información de 16 Mb/s con una portadora de 2,5 GHz puede transmitirse a través de un sistema de fibra óptica monomodo a 1550 nm de longitud de onda, consiguiendo una longitud máxima de 144 km con una magnitud de vector de error alrededor de 5,42% y una tasa de error de bit menor de 10^{-12}, empleando un bloque de SOA como preamplificador. Sin el uso de SOAs (configuración "*back-to-back*"), la distancia de transmisión alcanzada es de aproximadamente 92 km considerando idéntico límite de BER, con lo que se demuestra la mejoría en la longitud del enlace al utilizar SOAs sin cambios significativos en EVM.

La transmisión de datos digitales se realiza mediante un complejo sistema de modulación de amplitud en cuadratura (QAM) de 16 niveles, una técnica de modulación digital donde la información digital se encuentra contenida tanto en la amplitud como en la fase de la portadora transmitida, teniendo dos componentes ortogonales denominadas fase y cuadratura, y que se ha convertido en una atractiva candidata por su excelente eficiencia en ancho de banda, además de permitir alcanzar elevadas velocidades de transmisión de datos en un solo canal.

El montaje experimental se describe como sigue. En primer lugar, el generador vectorial (VSG) es empleado como fuente de señal, produciendo una señal de microondas operando a una velocidad de bit de 16 Mb/s y modulación QAM. Dicha señal modula una frecuencia de 2,5 GHz. La modulación óptica se realiza mediante el empleo de un láser DFB (Distributed Feedback), y la luz emitida es guiada mediante una fibra monomodo (SMF) hacia un atenuador variable que modela las pérdidas en el camino óptico, amplificada por un SOA y recibida por un convertidor de señal óptica, para ser finalmente estudiada y caracterizada en un analizador de señal vectorial (VSA).

La señal digital se escribe en código MatLab, de modo que el archivo creado correspondiente a las formas de onda en fase y cuadratura (*waveform file*) pueda ser descargado en el VSG y así creada la señal de microondas. En el sistema se incluye un ruido blanco aditivo gaussiano (AWGN) con una relación señal-ruido (SNR) de 20 dB, con el fin de simular el canal de ruido.

Previo al SOA se sitúa un controlador de polarización utilizado para reducir la reflexión inducida por el ruido de intensidad del láser de semiconductor (RIN), y un aislador óptico.

El SOA ofrece una amplificación de aproximadamente 24 dB en la ventana de operación de 1550 nm, cumpliendo con las especificaciones.

Otro aislador se inserta entre el SOA y el filtro óptico de banda estrecha centrado en 1547 nm. El filtro, precediendo al receptor y con un ancho de banda 3dB de 0,49 nm, reduce al mínimo el ruido ASE generado por el SOA, eliminando el ruido fuera de banda. El receptor óptico se utiliza para recoger la señal y su salida se conecta al VSA, donde la constelación, el espectro y otras mediciones como el EVM se muestran.

El experimento se lleva a cabo considerando tres escenarios diferentes, con el propósito de evaluar el efecto del amplificador incluido. Estas configuraciones son el montaje "*back-to-back*" (no incluye el SOA); y las estructuras de pre-amplificador óptico y amplificador en línea, dependiendo de la función del SOA del sistema. El principal objetivo es examinar los efectos de este dispositivo y evaluar la calidad del enlace de transmisión global, en términos de EVM en porcentaje de unidades rms (raíz media cuadrática), que puede ser utilizado para calcular la SNR en dB y la BER resultante.

Finalmente, se analizan las medidas y se concluye afirmando que con la inclusión de un bloque de SOA en la etapa receptora (preamplificador óptico) del sistema diseñado es posible alargar la distancia de transmisión del enlace óptico sin cambios significativos en el EVM y seguir cumpliendo las especificaciones de BER. De este modo, si se incluyeran diversos bloques de SOAs en cascada, se percibiría el efecto aún mayor en la longitud del enlace sin cambios en el EVM, aunque se observarían cambios importantes en el ruido ASE introducido por estos dispositivos, acumulativo a lo largo de las etapas. También se observa la función del amplificador SOA en línea, diseñado principalmente para compensar las pérdidas del enlace óptico.

UNIVERSITY OF LIMERICK

Date: **September 2008**

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Degree: ***Master Degree*** Year: ***2008***

To My beloved Parents, Jose and Cati,
and my adorable siblings Elena and Jose.

Table of Contents

List of Tables

List of Figures

List of Acronyms

AM	Amplitude Modulation
ASE	Amplified Spontaneous Emission
AWGN	Additive White Gaussian Noise
BER	Bit - Error – Rate
BPSK	Binary Phase Shift Keying
dB	decibels
dBm	decibels miliwatt
CNR	Carrier-to-noise ratio
CW	Continuous wave
DAC	Digital-to-Analog Converter
DFB	Distributed FeedBack
DSP	Digital Signal Processing
DVB-C	Digital Video Broadcasting-Cable
EVM	Error Vector Magnitude
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FM	Frequency Modulation
GHz	GigaHertz (frequency unit)
HDTV	High-Definition TV
I	In-phase
IF	Intermediate Frequency
ISI	InterSymbol Interference
km	kilometre
Mb/s (Mbps)	Megabits per second
PSK	Phase Shift Keying

ΦM	Pulse Modulation
Q	Quadrature
QAM	Quadrature Amplitude Modulation
RF	Radiofrequency
rms	Root mean square
RRC	Root Raised Cosine
SFDR	Spurious-Free Dynamic Range
SMF	Single- Mode-Fibre
SNR	Signal - to - Noise Ratio
SOA	Semiconductor Optical Amplifier
VSG	Vector Signal Generator
VSA	Vector Signal Analyzer
WDM	Wavelength Division Multiplexed

Abstract

This project presents an experiment based on a SOA-amplified haul microwave transmission by a radio-over-fibre system. Experimental results revealed that a 16Mb/s 16-QAM signal at a carrier of 2.5 GHz could be transmitted through a 1550 nm single-mode fibre-optic system, achieving a maximum link length of 144 km with an EVM around 5,42 % and a BER less than 10^{-12}, employing one SOA block as a preamplifier. Without the employment of any SOA block (back-to-back configuration), the transmission distance achieved was approximately 92 km with a BER less than 10^{-12}.

At first, the Vector Signal Generator (VSG) generates a microwave signal operating at a bit rate of 16 Mb/s and using a complex modulation scheme: Quadrature Amplitude Modulation (QAM). This microwave signal modulates a carrier frequency of 2.5 GHz. The emitted light signal is leaded to an attenuator which models the path loss, then amplified by a Semiconductor Optical Amplifier (SOA), received by a lightwave converter (sensitivity >200 V/W), and finally studied and characterized in a Vector Signal Analyzer (VSA).

The source signal corresponding to the digital modulation is initially written in MatLab code, so that the waveform file created can be downloaded onto the VSG. Furthermore, an additive white Gaussian noise (AWGN) with a Signal-to-Noise Ratio (SNR) of 20 dB is included in the system, so as to simulate the channel noise.

The overall experiment is carried out considering three different scenarios; with the purpose of evaluate the effect of the SOA included. These setups are the back-to-back configuration, without the inclusion of the SOA; and the optical pre-amplifier configuration and the in-line amplifier configuration, depending on the SOA function in the system. The main goal is to examine the effects of this device and evaluate the quality of the overall link performance, in terms of Error Vector Magnitude (EVM) in %rms units (Root Mean Square), which can be used to calculate the SNR in dB and the Bit Error Rate (BER), the expressions of which are found in **chapter 2 section 2**.

Acknowledgements

I have the pleasure to express my warmest thanks to my supervisor, Professor Michael Connelly. Without his guidance, support, ideas and contributions on studies on Optical Fibre Communication Systems this thesis would not have been completed properly. Many thanks for allow me to use the Optical Communications Laboratory and a great environment to set up the experiment.

I would like to give my sincere gratefulness for his assistance and valuable advice to Colm O'Riordan, who has contributed actively to clarify several aspects related to the components and devices with patience and kindness.

My appreciation also goes to Professor Tom Arbuckle, for his gentleness and his assistance when supervising me in my last exam of my master's degree, providing me with a wonderful atmosphere to carry it out.

I would like to express my profound gratitude to all the friends who have lived this unforgettable experience with me in Ireland, for their friendship, and for lifting my spirits in the hardest moments. Specially, thanks to Manu, Virginia, Francesc, Ester and Birkan for their support over the last two months in my project.

My achievements would not be possible without the help and love from my whole family. My highest and special thanks go to my parents, José and Cati, my sister Elena and my little brother, José, for encouraging me and giving me the opportunity to live this incredible experience and providing me with their whole support during my academic career.

Finally, give my special thanks to Raul, for his love and understanding, for believing in me and being by my side all the way through the last six years and thanks to all the people who have been involved in making my stay an extraordinary experience. No words can express my gratitude to them.

Chapter 1. Introduction

1.1. Thesis organization and main objectives

This Master Thesis mainly comprises three central parts to be discussed:

- On the one hand, a research labour is served in **chapter 1**, carried out in order to acquire and comprehend the theoretical background. Radio-over-fibre schemes and associated digital modulation formats (particularly 16-QAM), especially with regard to the use of Semiconductor Optical Amplifiers (SOA), are reviewed.
- On the other hand, an in-depth look at the equipment setup and capabilities of the VSG and VSA devices are covered in **chapter 2**. In addition, different performance metric definitions to assess the quality of digitally modulated systems are given. The theoretical signal-to-noise (SNR) and bit error rate (BER) expressions are presented as a function of the error vector magnitude (EVM) in **section 2.2.2**. One of the main goals of this project was to investigate the new software acquired by the Optical Communications Research Group of The University of Limerick, the VSG and VSA software, used to create and analyze modulation signals. Because of the darkness of the software help and the enormous quantity of functions and parameters insufficiently exposed, this process consumed a lot of time. In fact, the presence of the one-day orientation course about this software, provided by Agilent Technologies, should be advantageous.
- The last part, widely described in **chapter 3**, involves the experimental labour, where three different system implementations are performed.

The first section of this work illustrates how the QAM signal is created in Matlab code (**section 3.1**) and how it is generated using the arbitrary waveform generator provided by the VSG.

The second part (**section 3.2**) focuses on the experiment setups, considering different configurations of the SOA, and the last part (**section 3.3**) presents the discussion of the obtained results in the simulation. The effects of thermal noise, intrinsic laser intensity noise, and reflection-induced laser noise on the system performance are not taken into account in this paper

- Finally, chapter 4 summarizes the experimental results, derives conclusions and gives some suggestions for future research.

Objectives

To summarize, the goals of the experiment setups are to experimentally explore, investigate and interpret:

- The main characteristics and capabilities of the major components of the fibre optic communications system i.e. the source and transmitter (modulation formats, laser, VSG), the fibre channel (attenuation, spreading, etc.), the SOA and the receiver (lightwave converter and VSA).

- The overall system performance limitations imposed by the component characteristics:

- Maximum possible link length limited by attenuation
- Bit rate or symbol rate (and bandwidth)

- Optical communication system design and performance analysis in terms of EVM and BER.

1.2. Radio-over-Fibre Schemes

This section briefly introduces a radio over fibre communication system and deals with a particular digital modulation scheme: Quadrature Amplitude Modulation (QAM). It serves as a theory basis in order to understand the goals of this thesis and analyze the results better.

Over the past decade, transmission of microwave signals over optical fibres has been revealed to have a myriad of applications. For analog uses, for instance, externally modulated radio-over-fibre links have been considered very useful for microwave transmission systems owing to their low transmission loss and high compatibility with these systems. In addition, it is worth highlighting that radio-over-fibre links can also be used in applications such as distribution of digital HDTV (high-definition TV), or Hi-Fi radio, or even as optical/wireless interfaces in a fixed-wireless access network **[1, 2]**.

Fibre optic technology offers technical performance benefits over traditional coaxial feeds plus almost unlimited bandwidth and distance. They have attracted much attention due to its promising performance and operational cost reduction. Amongst the advantages should be mentioned: **[3]**

- Minimal attenuation losses (0,25 dB/km at 1550 nm wavelength)
- High dynamic range
- Large available bandwidth
- Immunity to electromagnetic interferences and eavesdropping
- Easy installation and maintenance
- Reduced power consumption

More in detail, a radio-over-fibre system refers to a fibre optic link where radiofrequency (RF) signals modulate an optical carrier, which is transmitted through the optical fibre link and subsequently carried towards the photo-detector in the receiver.

Traditionally, these systems use single-mode-fibre (SMF) as transmitter medium. This is because for the typically narrow-band RF signals, the SMF can be regarded as a nearly ideal transmission medium with virtually no loss or distortion. Only at very high frequencies or very long link distances does the chromatic dispersion of SMF become perceptible, which contributes additional distortion. To date, therefore, all available high-frequency and high-performance analog fibre-optic systems have been based on SMF **[4]**.

Due to its excellent bandwidth efficiency, vector modulation techniques are extensively used for these proposed fibre radio links **[5,6].** For transmitting digital data, the best known performance with respect to channel efficiency is achieved with quadrature amplitude modulation (QAM), a kind of digital modulation that has become an attractive candidate for its spectral efficiency and which permits achieving high data rates in a single channel.

1.3. Quadrature Amplitude Modulation

As mentioned, QAM systems are widely used in modern communication systems where maximum throughput is required under limited bandwidth conditions, thus being considered an alternative way of increasing the spectral efficiency in optical communications. Furthermore, the benefits of M-QAM have been widely accepted for microwave digital radio applications and voiceband modems, including Digital Video broadcasting-Cable (DVB-C), in addition to wireless 802.11 protocols or personal communications for the military **[7]**.

1.3.1. QAM overview

In general terms, QAM can be defined as the digital modulation format where information is conveyed in the amplitude and phase of a carrier signal.

This scheme combines two carriers whose amplitudes are modulated independently with the same optical frequency and whose phases are shifted by 90 degrees with respect to each other. These carriers are called in-phase carriers (I) and quadrature-phase carriers (Q).

An *M-ary quadrature amplitude modulation* (*M*-QAM) signal can be defined by the following equation:

$$s_m(t) = A_m \cdot g(t) \cdot \cos(2\pi f_c t + \theta_m) \qquad m = 1,2,...,M \tag{1.1}$$

where $s_m(t)$ represents the bandpass signal chosen from the M possible waveforms, f_c symbolizes the carrier frequency, *g(t)* is a real-valued signal pulse whose shape influences the spectrum of the transmitted signal (the detailed characteristics of this function is given in **section 1.3.3**), and A_m and θ_m denote the amplitude and phase angle of the m^{th} symbol, given by

$$\begin{aligned} A_m &= \sqrt{\left(A_m^I\right)^2 + \left(A_m^Q\right)^2} \\ \theta_m &= \tan^{-1}\left(\frac{A_m^Q}{A_m^I}\right) \qquad m = 1,2,...,M \end{aligned} \tag{1.2}$$

In these equations, $A_m{}^I$ and $A_m{}^Q \in \{\pm 1d, \pm 3d, ..., \pm(M-1)d\}$ indicate the I and Q amplitudes corresponding to the *M* possible symbols in the two-dimensional space (see *fig. 1.1.* for a 16-QAM) and *d* is a constant whose value is determined by the average transmitted power.

Otherwise, the bandpass QAM signal in (1.1) can be expressed equivalently in terms of its in-phase and quadrature components as follows:

$$s_m(t) = A_m^I \cdot g(t) \cdot \cos(2\pi f_c t) - A_m^Q \cdot g(t) \cdot \sin(2\pi f_c t) \qquad m = 1,2,...,M \tag{1.3}$$

The transmitted bandpass signal $s(t)$, which contains all the symbols represented by the M possible signalling waveforms for QAM, can be expressed as **[8]**:

$$s(t) = \mathrm{Re}\left\{ \left(\sum_n I_n \cdot g(t - nT_s) \right) \cdot e^{j2\pi f_c t} \right\} \qquad (1.4)$$

where T_s refers to the symbol duration, ($R_s = 1 / T_s$ indicates the transmission rate in symbols/second) and $\{I_n\}$ represents the discrete information-bearing sequence of symbols and is complex-valued for QAM.

16-QAM

16-state Quadrature Amplitude Modulation (16-QAM) is a QAM with M=16 voltage levels or possible states for the signal, that is, four *I* values and four *Q* values. QAM transmits k bits of information during each symbol period, where $k = \log_2 M = 4$ bits, that is $M = 2^k$, consisting of two bits for *I* and two bits for *Q*. The symbol rate is one fourth of the bit rate, producing a very spectrally efficient transmission.

Generally, the mapping of the bits into symbols is carried out in Gray code, so as to minimize the number of bit errors occurring for every symbol error. In Gray-coding, the bit assignment pattern is performed in a way that adjacent symbols only differ by one bit.

In the next figure, the rectangular constellation of an unfiltered 16-QAM signal is presented (see **section 2.2.2.1** for a detailed description about constellation diagrams).

The 16 symbols in the constellation diagram are equally spaced and independent, and each is represented by a unique combination of amplitude and phase.

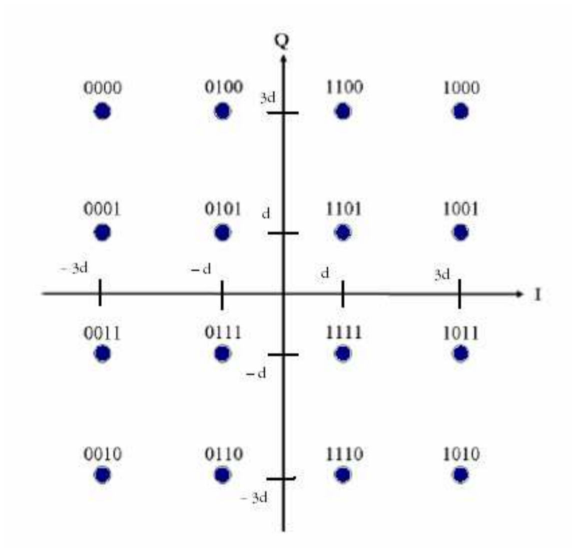


Fig.1.1.Rectangular constellation of a Gray-coded 16-QAM signal

Below, an example of the ideal I and Q waveforms in a 16-QAM signal, with the amplitude levels and phase variations between symbols, is depicted.

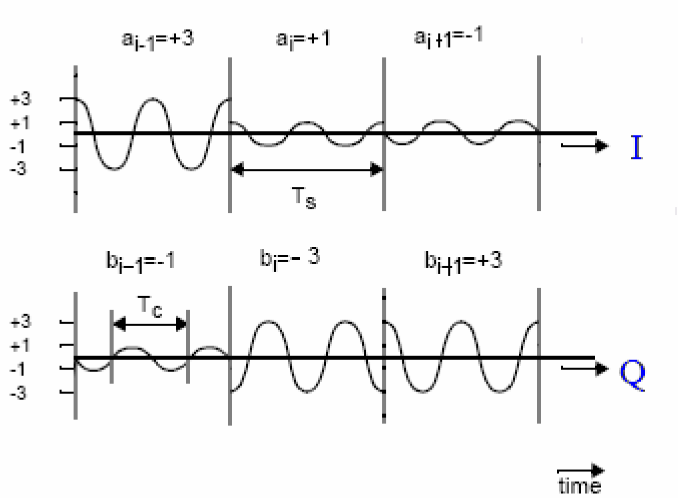


Fig.1.2. 16-QAM in time domain

QAM Generation

The easiest way to generate a 16-QAM signal is illustrated in the block diagram below. It is viewed as two quadrature amplitude modulated carriers, with levels ±d and ±3d, giving 16 possible combinations of symbols at the transmitter output.

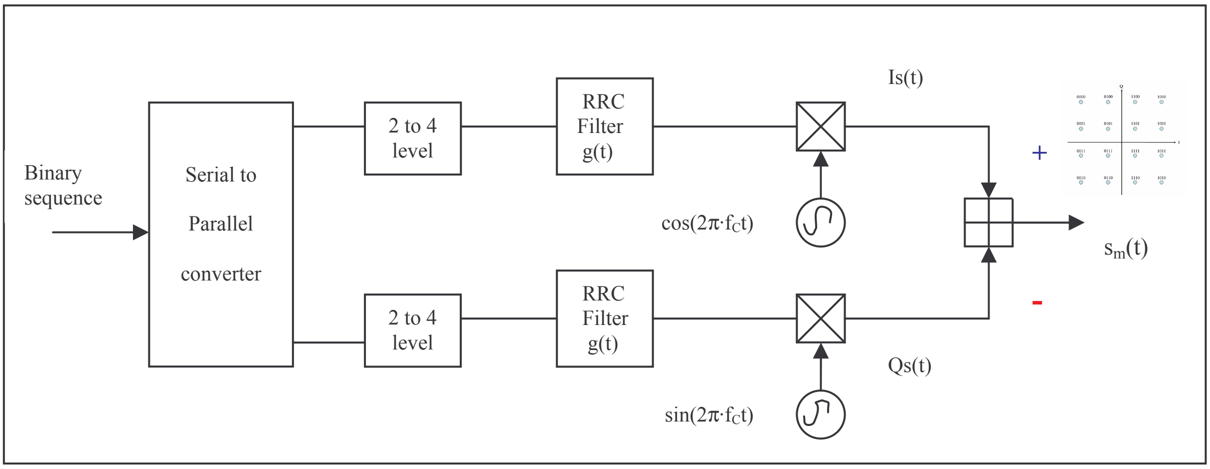


Fig.1.3.Typical QAM modulator

As described subsequently, pulse shaping is achieved by filtering the multi-level baseband input symbol streams. There are two filters *g(t)*; one each for the *I* and *Q* channels, in order to create a compact and spectrally efficient signal that can be placed on a carrier.

Finally, so as to detect the two waves at the receiver, the modulator uses the orthogonality property of the sine and cosine carriers, and the modulated signal is obtained.

1.3.2. Filtering

In a microwave system, data signal bandwidth reduction plays an important role in increasing the spectral efficiency. The advantage of filtering in the transmitter is that it allows the transmitted bandwidth to be significantly reduced without losing the content of the digital data.

By shaping the data pulses, so as to smooth the edges (in *I* and *Q*) and slow down the fast transitions between states, the high frequency spectral content of the waveform is considerably decreased. Furthermore, filtering reduces interference because it reduces the tendency of one signal or one transmitter to interfere with another in a Frequency-Division-Multiple-Access (FDMA) system **[9]**.

Thus, selecting the best filter becomes a design compromise between spectral efficiency and minimizing ISI. Although there are many available filter types used in digital communications, Nyquist filters have been widely used in microwave transmission systems to achieve this purpose. It is well known in microwave communication that a Nyquist filter is especially useful for reducing the bandwidth of the data signal without introducing Intersymbol interference (ISI) **[10]**, since they strongly filter the signal without blurring the symbols together at the symbol times, thus minimizing ISI. This is a valuable property when transmitting information without errors originated by ISI.

Amongst the different kinds of filters, the most common are listed below:

- Raised Cosine (RC)
- Square-root raised cosine (RRC)
- Gaussian filters

It must be also mentioned the importance of improving the overall performance of the system by also filtering at the receiver end, in order to remove strong signal interferers and also reject as much noise as possible. So due to the reduced bandwidth, sensitivity at the receiver end is enhanced.

Nyquist or raised cosine filter family

A commonly used pulse-shaping method is to pass the data stream through a low pass filter having a raised cosine response. The raised cosine filter belongs to the family of Nyquist filters, those which have particularly useful properties in data communications.

As mentioned, the essential property of Nyquist filters is that their impulse response rings at the symbol rate, which means that the filter is chosen to have its impulse response cross through zero, at the symbol clock frequency. Moreover, the ringing depend on the roll-off factor (defined in next subsection), also called alpha (α). The smaller value of α, the more pronounced the ringing as the filter response approaches that of the ideal brick-wall filter (α = 0).

Below is given the mathematical expression of the frequency response of a RC **[11]**:

$$H_{RRC}(f)=\begin{cases} T & |f|\le\frac{1-\alpha}{2T_s} \\ \frac{T}{2}\left[1-\sin\left(\left(|f|-\frac{1}{2T}\right)\frac{\pi T}{\alpha}\right)\right] & \frac{1-\alpha}{2T_s}\le|f|\le\frac{1+\alpha}{2T_s} \\ 0 & |f|\ge\frac{1+\alpha}{2T_s}\end{cases} \tag{1.5}$$

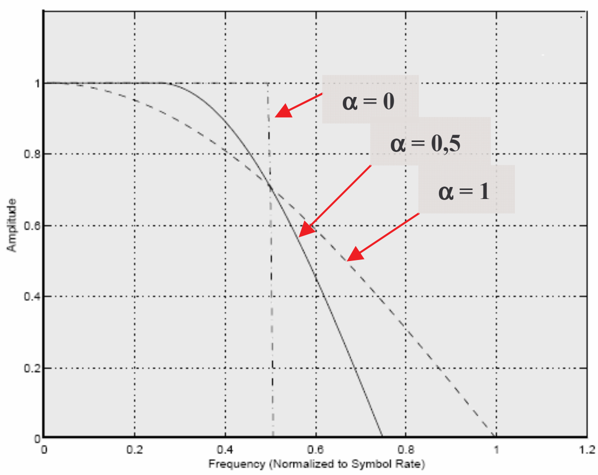


Fig.1.5.Frequency response of a Root-raised cosine filter for different values of alpha (α)

The time-domain function of the filter is a sinc function:

$$h_{RRC}(t) = \sin c\left(\frac{t}{T}\right) \cdot \frac{\cos\left(\frac{\pi\alpha \cdot t}{T}\right)}{1-\left(\frac{2\alpha t}{T}\right)^2} \qquad (1.6)$$

Where T defines the symbol duration and α the roll-off factor.

Figure 1.4 shows the impulse or time-domain response of a RC filter, where the effect of the α chosen on the impulse response is illustrated, as it varies between 0 and 1. As seen, the time-domain ripple level increases as α decreases, indicating that the excess bandwidth of the filter can be reduced, but only at the expense of an elongated impulse response **[12]**.

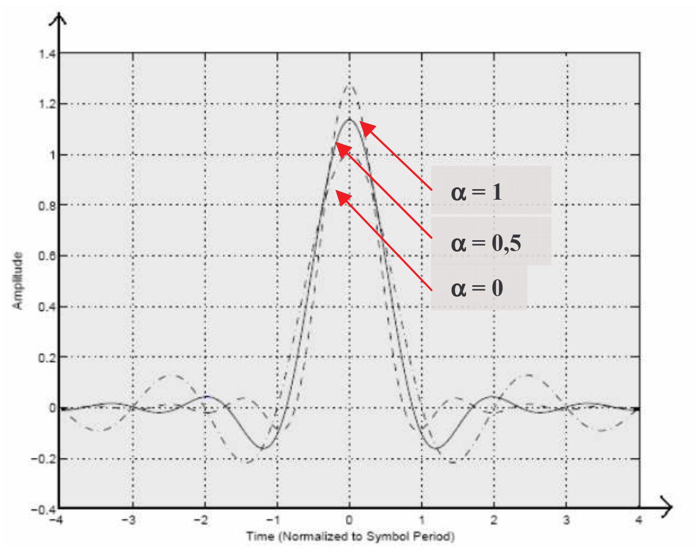


Fig.1.4. Impulse response of the Root-raised cosine filter for different values of alpha (α)

As discussed, by plotting the impulse response of the filter, the spreading (ISI) effect of a raised cosine filter on the data pulses passing through it can be estimated.

More in detail, the time response of the filter goes through zero with a period that exactly corresponds to the symbol spacing and has its peak amplitude at the t = 0 instant. Due to the fact that the response equals zero at all symbol times except the centre one, there is no interference between adjacent symbols at these instants.

Therefore, the conventional way to deal with ISI will be to accept overlap, but carefully shape the pulses so that overlapping pulse waveforms have zero amplitude at each decision-making instant.

The roll-off factor alpha

The sharpness of a raised cosine filter is controlled by the parameter alpha (α), also called roll-off factor or excess bandwidth factor. This parameter is defined to be the fraction of bandwidth over the minimum required for ISI avoidance at a given symbol rate, thus giving a direct measure of the occupied bandwidth of the system. It is calculated as follows **[10]**:

$$Occupied\_BW = symbol\_rate \cdot (1+\alpha) \quad (1.7)$$

Two extreme situations can be studied from this equation:

- If the filter had an ideal characteristic with sharp transitions and an ***alpha=0*** (brick wall filter), the occupied bandwidth would be,

  $$Occupied\_bandwidth = symbol\ rate \cdot (1 + 0) = symbol\ rate$$

  In the ideal situation, the occupied bandwidth would be the same as the symbol rate, but this is not practical, since a roll-off factor of zero is unachievable.

- Consider the other case, a broader filter with an ***alpha =1***, easier to implement. The occupied bandwidth would be,

  $$Occupied\_bandwidth = symbol\ rate \cdot (1 + 1) = 2 \cdot symbol\ rate$$

This means that an excess bandwidth factor of one uses twice as much bandwidth as an alpha of zero.

In practice, it is possible to implement an alpha below 0.2 and make good, compact, practical radios, although typical values range from 0.35 to 0.5. In this experiment, the chosen value for alpha results to be 0.5, which means that it will use 50% more occupied bandwidth than the theoretical minimum, fixed to one half the symbol rate.
The chosen value must provide a good compromise between spectral efficiency and minimum ISI. In *Table 1.1* are listed the premises to follow to choose a good alpha.

Choice of the roll-off factor

Table 1.1.Choice of the roll-off factor **[13]**

Advantages of small roll-off	**Advantages of large roll-off**
Maximum bandwidth efficiency achieved	Simpler filter – fewer stages (taps) hence easier to implement with less processing delay
	Less signal overshoot, resulting in lower peak to mean excursions of the transmitted signal
	Less sensitivity to symbol timing accuracy – wider eye opening

Transmitter-receiver matched filters

Filtering is usually performed at both the transmitter and the receiver; performing a "matched filter" arrangement which gives optimal received SNR in white noise.
In this case, it is said that the square-root Nyquist filter in the transmitter has a matched response located in the receiver.

Particularly, filtering in the transmitter reduces the adjacent-channel-power radiation, and thus the possibility of interfering with other transmitters; whereas filtering in the receiver reduces the effects of broadband noise and also interference from other transmitters in nearby channels.

To obtain an ideally zero ISI, both filters must be designed satisfying the expression below, in which the combined matched filters must give a Nyquist filter response for all the system:

$$H_R(f) \cdot H_T(f) = H(f) \tag{1.8}$$

And, as a result:

$$|H_R(f)| = |H_T(f)| = \sqrt{|H(f)|} \tag{1.9}$$

Where $H_R(f)$ and $H_T(f)$ are the frequency response of the transmit and receive filters, and $H(f)$ corresponds to the overall frequency response of the system.

If the design is performed correctly the results are the best data rate, the most efficient radio, and reduced effects of interference and noise.

QAM Spectrum

As can be noticed in equation 1.1, the signal spectrum is directly related to the frequency response given by the filter.

In *Fig.1.6.*, a series of four ideal QAM spectra is depicted, depending on the filter used in the pulse shaping (for more detail, explore the **section 2.2.2.3**.), and all with the same symbol rate, normalized to 1. In plot (a), a perfect brick-wall rectangular spectrum is shown. As the magnitude response of a matched filter, this signal is unrealizable in practice because the pulse-shaping filter in the transmitter would have to be infinitely long in time duration. This graph also represents the power spectrum of the waveform transmitted using such an ideal filter. Despite its impracticability, it is useful as an illustration of an ideal situation in which the occupied bandwidth equals the symbol rate and there is no excess bandwidth **[14]**.

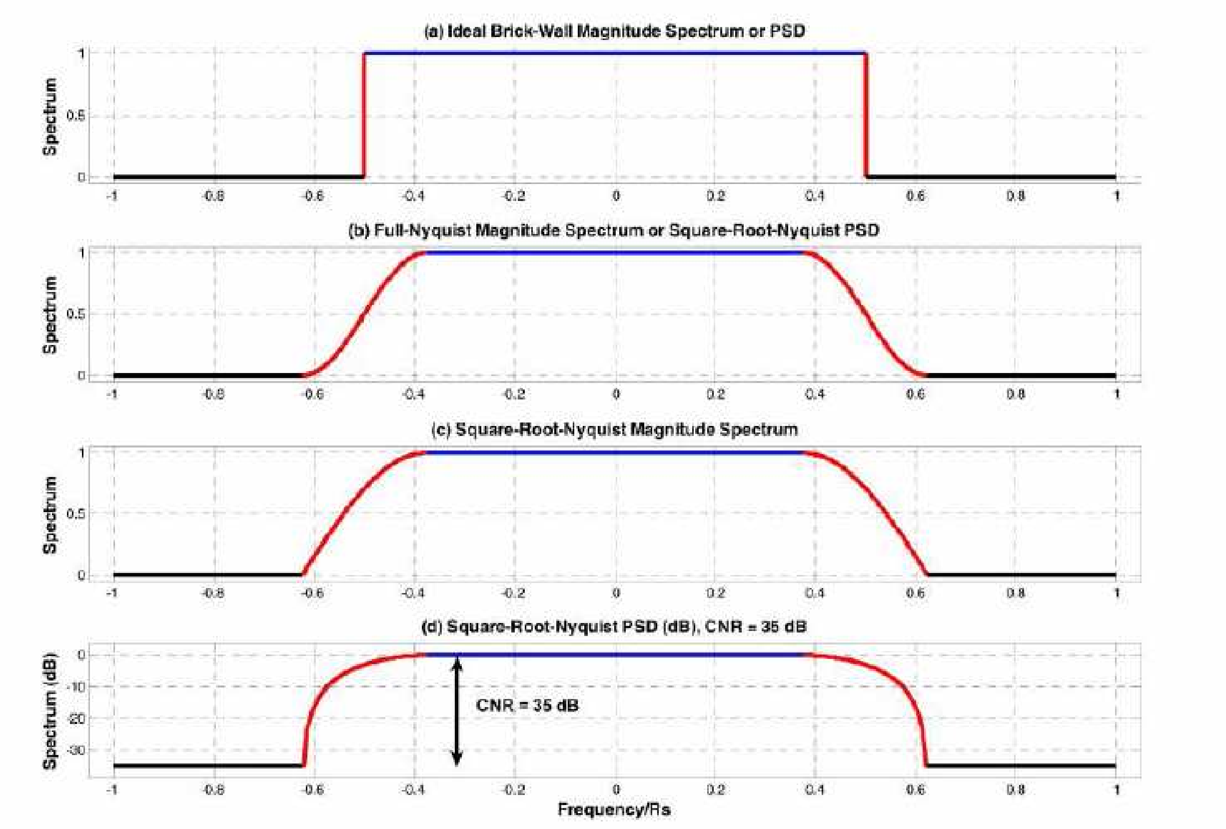


Fig.1.6. Ideal QAM Spectrum plots (a)Ideal Brick-wall Magnitude spectrum,(b) Full Nyquist-Magnitude Spectrum or Square Root-Nyquist PSD, (c) Square Root- Nyquist Magnitude Spectrum, (d) Square-Root-Nyquist PSD, CNR = 35 dB (carrier to noise ratio)

1.4. SOAs and applications

1.4.1. Introduction about optical amplification

When the light propagates down a fibre optic cable, two phenomena affect its behaviour: **attenuation** and **dispersion**.

Dispersion essentially affects the fibre bandwidth, causing optical pulse broadening and consequently, intersymbol interference, which leads to an increase in the system BER. Attenuation, in contrast, reduces the optical power available, degrading the error probability, and affecting the limit distance, as a result of the signal power loss.

The attenuation curve of conventional single-mode silica fibre, shown in *Fig. 1.7*, illustrates the variation of attenuation with wavelength over an optical fibre. The three main windows of operation are 850 nm, 1300 nm and 1550 nm, which correspond to wavelength regions where the attenuation curve has minimums.

The absolute minimum is located in the 1550 nm wavelength region. As shown in the figure, attenuation falls when increasing wavelength, so the loss at 1550 nm is only about 0.25 dB/km, compared to about 2.5 dB/km at 850 nm. The peaks in the figure are caused by impurities in the fabrication process.

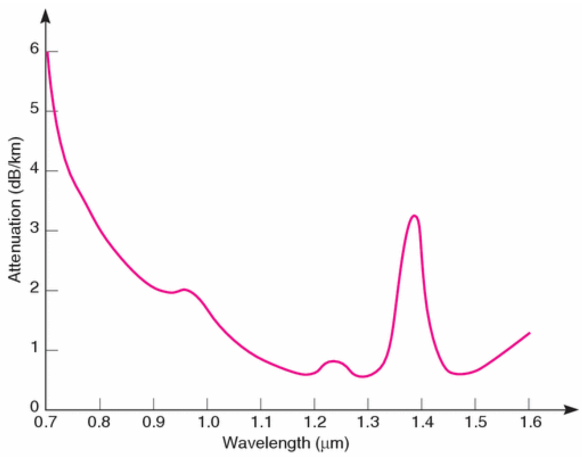


Fig.1.7. Fibre attenuation [dB/km] curve for pure silica glass

Referring to the dispersion phenomenon, it must be stated that the dispersion spectrum of conventional single-mode silica fibre has a minimum in the 1.300 nm region.

Since the attenuation and material dispersion minima are located in the second and third 'windows', these are the main wavelength regions used in commercial optical fibre communication systems.

Due to the signal degradation factors mentioned, signal regeneration is considered one of the critical functions for the future long hauls in all optical networks.

Early fibre-optic telecommunication systems included signal **repeaters** that consisted of a detector, amplifier, and a signal regenerator that restored the shape and intensity of the pulses. These devices were used to extend the length of optical links, by overcoming loss due the attenuation and distortion, and were based on the following principles: regenerating an optical signal by converting it to an electrical signal, processing it and then retransmitting the optical signal again.

In the more modern networks and long-haul systems, the repeaters have been replaced by **optical amplifiers**, which consist of laser gain material that replicate and reinforce the signal optically. These devices amplify the optical signal directly, without the previous conversion to an electrical signal, and are based on the stimulated emission principle in the gain's medium, so as to cause the amplification of the incoming light. In estimulated emission, matter may lose energy when perturbed by a photon, resulting in the creation of another photon. The perturbing photon is not destroyed in the process, and the generated photon has the same phase, frequency, polarization, and direction of travel as the original.

The main advantage of these over the repeaters is that they can be used for many wavelengths in Wavelength Division Muliplexing (WDM) systems at a relatively low cost, amplifying all of the wavelengths in a single device. In contrast, an optical amplifier cannot perform the regeneration function, as the repeaters do, but generally, the limiting factor in the design of a communications system is the attenuation, rather than distortion**. [15, 16]**

It is worth mentioning two principal types of optical amplifiers which are being used at present: The Semiconductor Optical Amplifier (SOA) and the Optical Fibre Amplifier (OFA), of which must be mentioned the Erbium-Dopped Fibre Amplifier (EDFA) **[17-22]**. Even though it its true that the latter has been used more frequently in recent times, the interest for the use of SOAs has increased considerably, as basic amplifiers and also as functional elements in optical communication systems and optical signal processing devices **[23]**. In this experiment, a SOA from Kamelian Ltd. will be used.

1.4.2. SOA fundamentals

Overview

According to Wikipedia **[16]** , SOAs are defined as amplifiers which utilize a semiconductor to provide the gain medium and possess a similar structure to Fabry-Perot laser diodes but with anti-reflection design elements at the endfaces.

Generally, SOAs are made from group III-V compound semiconductors, using elements such as Ga, As, Al, In, or P, although any direct band gap semiconductors such as II-VI could be used in practice. Such devices operate at signal wavelengths between 850 nm and 1.600 nm and are capable of generating gains of up to 30 dB, thus being often used in telecommunication systems as fibre-pigtailed components.

A schematic illustration of the structure of a SOA is shown below. The electrical current represented is needed in order to produce the gain amplification. By means of stimulated emission, the input light signal is amplified in the active region, but this gain process is accompanied by an additive noise at the output, called amplified spontaneous emission (ASE). The waveguide serves as a confinement medium, so as to lead the propagating signal to the active region.
Further and great research about these devices is provided in **[23, 24]**.

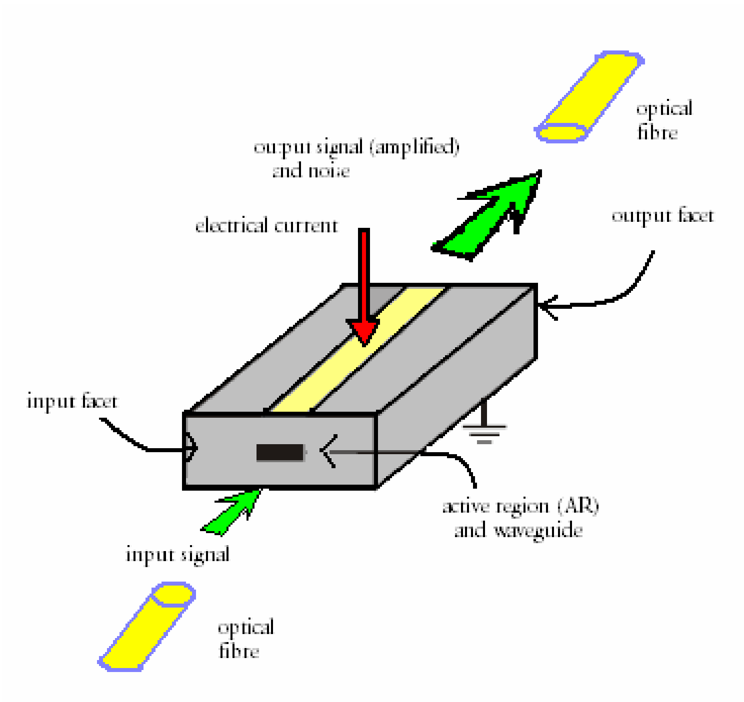


Fig. 1.8. Schematic diagram of a SOA

Comparison of Optical Amplifiers: SOA versus EDFA

The advantages of a SOA over an EDFA are listed below:

- it possesses small dimensions
- it is pumped by a DC current
- it provides the capability of being designed for any wavelength of interest
- it can be integrated with electro-optic semiconductor components
- it can be potentially less expensive than the EDFA.

Nevertheless, the main advantage of the EDFA is its performance. In EDFA there is no coupling loss to the transmission fibre, it is polarization-insensitive, it has lower noise than SLAs, it can be operated at saturation with no intermodulation (owing to the long time constant of the gain dynamics), and it can be integrated with fibre devices. However, it does require optical pumping, with the principal pump wavelengths being either 980 or 1480 nm **[24]**.

1.4.3. SOA Applications

Owing to recent enhancements in optical semiconductor fabrication techniques and device design, the SOA is showing great potential for use in evolving optical communication networks, emerging as an important component in many optical signal processing systems, optical fibre communication and switching **[23]**.

In addition to its basic purpose as an in-line amplifier, to overcome fibre losses, SOAs have become very attractive for a huge number of applications. They can be utilised as general gain elements but due to latest research on these devices, they have been found very useful in numerous functional appliances including optical switching, wavelength conversion, clock recovery, signal demultiplexing, and pattern recognition. Some of these applications, where there is no conversion of optical signals into the electrical domain, are required in transparent optical networks

The main system applications performed by SOAs, depending on the placement of the device in the transmission system, are explained below:

a. Power booster

The main utility of a SOA used as a power booster is to improve the power input signal prior to transmission. By means of increasing the laser power in an optical transmitter, medium-haul links with increased transmission length can be realizable.

In long-haul links the use of a booster amplifier can increase the link power budget and reduce the number of in-line amplifiers or regenerators required.

There are two possible scenarios of interest considering this purpose, in which SOAs prove their advantages. These are explained in the next page.

- ***back-to-back configuration***, in which links simply consist of an optical fibre between the transmitter and receiver. It excludes the SOA but includes the effect of the transmission link. As this involves no active components in the transmission link, reliability and performance are enhanced.

- ***Booster amplifiers*** followed by a single mode fibre are also useful in distribution networks, where there is a growing need to manage the increase in loss budgets associated with optical networks comprising optical nodes, large splitting losses or a large number of taps. Booster amplifiers are also necessary in WDM transmission, when it is required to simultaneously amplify a number of input signals at different wavelengths. In this kind of networks, maximum flexibility and utilisation of the wavelength resource is required. The ability to perform a limited amount of channel power equalisation on each wavelength in a WDM multiplex is of benefit.

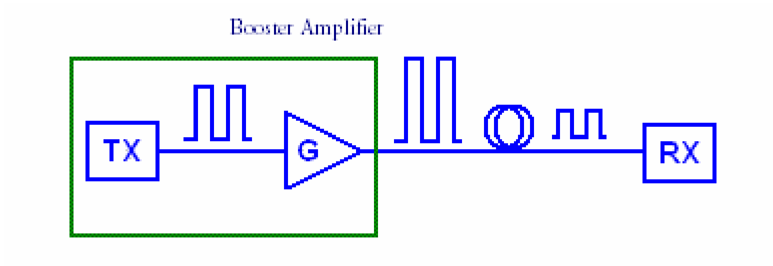


Fig.1.9. SOA as a booster amplifier in a SMF link

b. Optical preamplifier

Practical optical receivers introduce thermal noise into a communications link, in a way that error free detection of the incoming optical data signal is not possible below a minimum receiver power. This minimum power is typically characterised by the receiver sensitivity, which defines the received signal strength for a particular BER.

The use of an optical amplifier prior to a receiver to boost the signal power enables error free operation to be obtained for considerably reduced signal powers at the input to the optical amplifier. Optical isolators and/or filters can be used under certain circumstances to improve receiver sensitivity but at the expense of cost and complexity.

In this mode the SOA also provides a signal equalisation function, effectively providing automatic gain control directly in the optical domain which is relevant, for example, in network fault conditions where the increase in optical power incident on the receiver may cause damage **[25]**.

To summarize, it can be stated that the purpose of an optical preamplifier is to increase the power level of an optical data signal before to detection and demodulation, so as to enhance the receiver sensitivity and allow longer links to be constructed without the use of repeaters.

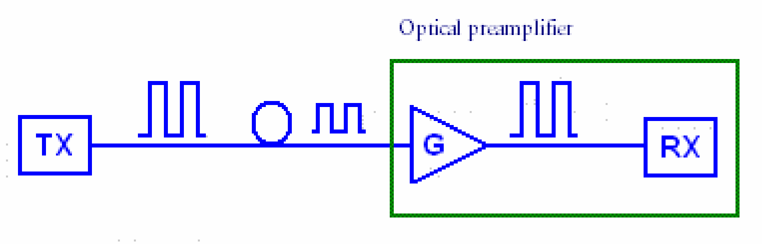


Fig.1.10. SOA as an optical preamplifier in a SMF link

c. In-line amplifier

In-line optical amplifiers are used in loss limited optical communication systems to increase the signal power and compensate for fibre losses, thus overcoming the need for optical regeneration.
As the in-line amplifier has only to amplify the input signal, instead of performing a full regeneration, it is intrinsically a more reliable and less expensive device.

Frequently, in-line amplifiers are used in groups, in a cascade configuration, being distributed through the SMF with the same distance between each other.

The main advantages of in-line SOAs are **[23]**:

- Transparency to data rate and modulation format
- Bidirectional
- WDM capability
- Simple mode of operation
- Low power consumption
- Compactness

The latter 2 points are considerably important, because they are used for remotely located optical components.

Fig.1.11. illustrates a basic system with a SOA working as single in-line amplifier.

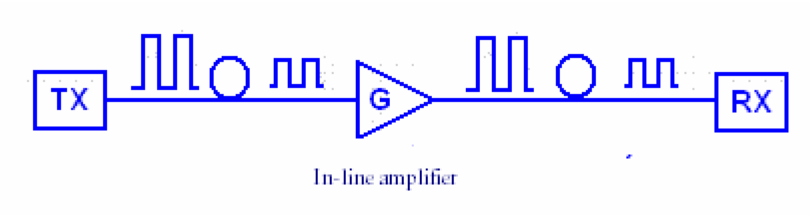


Fig.1.11. SOA as an in-line amplifier in a SMF link

Chapter 2. The equipment

In this chapter, the basic principles of operation and the main utilities and characteristics of the VSG and VSA are discussed, along with the most useful features taken into consideration in this project.

2.1. Vector Signal Generator (VSG)

2.1.1. Overview

The N5182 signal generator is a vector model which offers a wide range of digital modulation capabilities for research and development, manufacturing or troubleshooting applications. Providing a comprehensive feature set, it generates standard and custom digital modulation formats, filtering and burst shapes; in addition to versatile analog modulation, with exceptional quality, reliability and worldwide support. One of the main advantages, as will be discussed in next page, is the possibility to download arbitrary signals from Matlab software.

The main features, useful for this master thesis, are listed below:

- 100 kHz to 6 GHz frequency range with a resolution of 0,01
- Automatic levelling control (ALC); power calibration
- GPIB, USB 2.0, and 100Base-T LAN interfaces
- Analog modulations AM, FM, and ΦM; pulse modulation and step/list sweep mode
- Arbitrary I/Q waveform playback up to 125 Msamples/second (Option 654)
- Maximum available output power range of -110 dBm to +10 dBm at 2,5 GHz, with a resolution of 0,02
- Baseband modulation bandwidth up to 100 MHz
- Effective DAC resolution 11 bits
- Arbitrary waveform memory:
    - Maximum playback capacity of 8 Msa, 64 Msa (Option 019)
    - Maximum storage capacity of 100 Msa

Digitally modulated signals can be created by clocking the Digital-to-Analog Converter (DAC) with the symbols transmitted, passing the DAC output through a pre-modulation filter (to reduce the transmitted bandwidth), and then modulating the carrier with the filtered signal.

So as to perform this function, the VSG includes a utility called dual ARB waveform player, which makes possible to download a waveform by means of the USB interface and Matlab software, and modulate a continuous wave (CW) signal with an arbitrary I/Q waveform. This means that, once a waveform has been created, it can be stored and recalled, which enables repeatable playback of test signals.

Fig. 2.1. VSG Front panel

2.1.2. Waveform File Fundamentals

The generation of this file will be reviewed with more detail in **section 3.1**. Here, only the basics and characteristics related to the equipment in this issue will be explained.

In general terms, the waveform file is defined as the set of I/Q samples that define the waveform. In the VSG there are two types of waveform files:

- **Segment**: Waveform file that the user downloads to the signal generator
- **Sequence**: File created in the VSG that contains pointers to one or more waveform files (segments, other sequences, or both)

In this work, the I/Q data created with Matlab code is treated as a waveform segment in the VSG, loaded from the external USB media and played by means of the dual ARB waveform player. The steps to follow in order to achieve this goal are listed next **[26]**:

Playing a Waveform Segment

1. Press **Mode** > **Dual ARB** > **Select Waveform**.
2. In the Segment on USB Media column, highlight the waveform segment to play.
3. Press **Select Waveform**.
4. Set **ARB Off On** to On.
5. Configure the RF Output

Steps 1 to 4 play the selected waveform segment, turning on both the I/Q and ARB enunciators, and the waveform modulates the RF carrier. In step 5 the RF carrier frequency and amplitude are set, and the RF output is turned on, making available the waveform segment at the signal generator's RF Output connector.

In the picture below, a schematic menu of the waveform segment softkeys is shown.

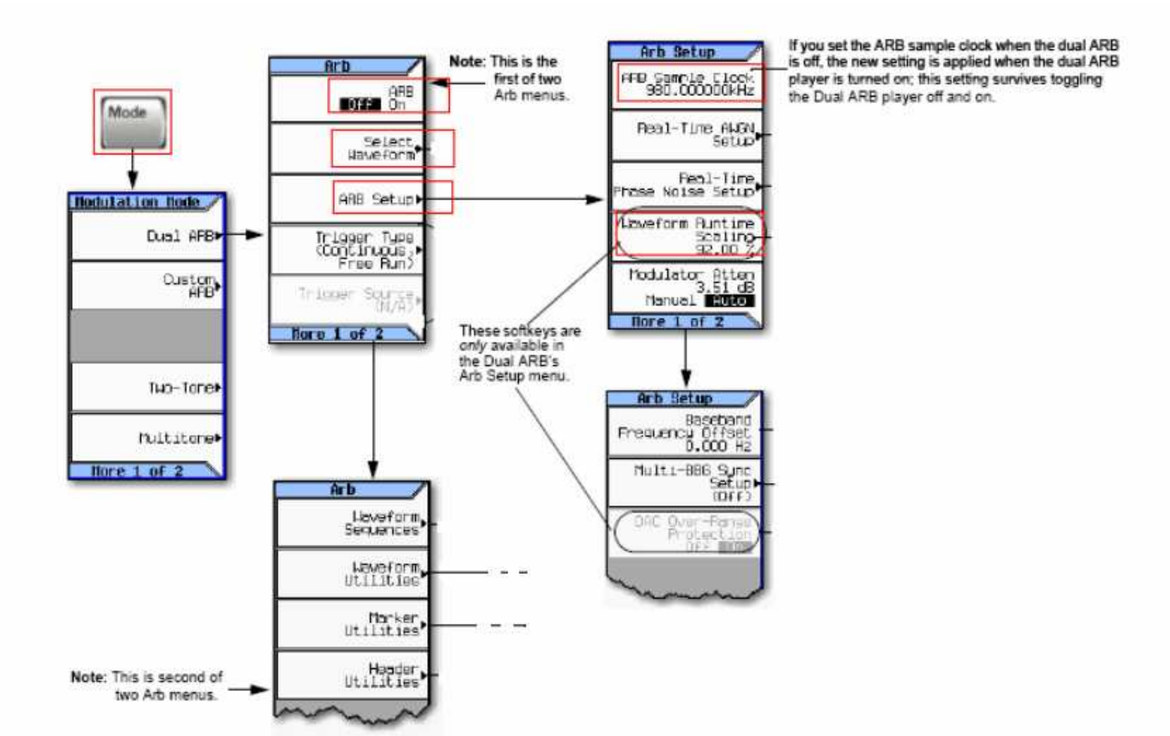


Fig. 2.2. Waveform Segment Softkey.s The frequently used keys are high lightened in red box.

2.2. Vector Signal Analyzer (VSA)

2.2.1. Overview

The Agilent 89600 Series VSA software, provided by the MXA N9020A instrument, is an advanced tool which allows the user to employ complete functionalities for the study and monitoring of complex-modulated RF and microwave signals.

On the one hand, this software integrates detailed spectrum analyzer measurements with advanced digital vector signal analysis, thus providing the ability to vector detect an input signal and optimizing speed, accuracy, and dynamic range.

On the other hand, it is an analysis system that delivers precise modulation measurements on the digitized signals found in today's DSP-based radio transceivers used in many purposes, including cell phones, base stations, satellite and military communication systems, or radar applications.

Moreover, Agilent Digital VSA technology is considered a powerful tool versus other typical spectrum analyzers with demodulation capabilities, because it can be used to evaluate simulation results, recognize and track down design problems before they become hardware problems, hence becoming very useful in RF and wireless communication applications.

Fig. 2.3. VSA Front Panel

The analyzer includes a Windows XP Pro® built in as and operating system, which expands the usability of the analyzer and provides the user with a comfortable and 'easy-to-use' interface to interact.

The VSA also relies on a PC for its processing, allowing the user to know the functionality of a complete system. Data can come from several sources, including multiple supported hardware platforms, recorded files or from Matlab software, as it was done in this project, and by means of the GPIB bus and a signal generator.

In the table below are summarized the main features and test capabilities of Agilent Digital VSA software **[27]**:

Table 2.1. Main solutions provided by the Agilent Digital VSA software
Analyses of the digital baseband or digital IF signal in a variety of different formats, including scalar baseband, scalar IF, complex I&Q, magnitude and phase, and phase only.
Flexible demodulations that measure carrier offset, error vector magnitude (EVM) and frequency error for QPSK, QAM, GSM, EDGE, WiMAX, W-CDMA and others.
Multiple display formats, including phase vs. time, frequency vs. time, and spectrogram, for rapid insight into complex signal behaviour.

2.2.2. Measurements

In this section, the major measurements taken into account in the experiment, such as constellation diagrams, EVM magnitude and spectrum are reviewed. The Agilent literature texts **[28-30]** are recommended for further in-depth study**.**

2.2.2.1. Constellation diagrams

There are numerous ways to view a digitally modulated and demodulated signal. In order to facilitate the visualization of demodulated signals, constellation diagrams are often used to represent digital bits in terms of symbols. They are considered the bridge between digital and analogue representations of a data stream.

On the one hand, considering the digital aspect of the constellation diagram, it is a plot of symbols where each symbol contains one or more bits (depending on the modulation scheme). On the other hand, considering the analog aspect, the constellation diagram displays the symbols at the decision points, where each symbol is represented by a unique magnitude and phase, thus presenting phase and magnitude errors, at the decision points. As it will be demonstrated, constellation diagrams provide insight into varying power levels, the effects of filtering, and impairments such as ISI.

The relationship between constellation points and bits per symbol is as follows:

$$M = 2^k \tag{2.1}$$

where M = number of constellation points
k = number of bits contained in a symbol

Another way to represent the same expression:

$$k = \log_2 M \tag{2.2}$$

*Fig.2.4.***[29]** shows three constellation diagrams for 16QAM. As described in **section 1.2.**, *I* and *Q* represent the in-phase (0°relative phase) and quadrature (90°relative phase) values of each symbol, thus providing each symbol with a resulting magnitude and phase.

A measured set of symbols is depicted in *Fig.2.4.(a)*. The V_I and V_Q axes give, respectively, the measured in-phase and quadrature (90°relative phase) voltage levels for a complex voltage representation. The effect of small errors in the measured symbols is indicated by the scattered dots. *Fig.2.4.(b)* represents the ideal constellation described below.

The diagrams in Figs. *2.4.(a)* and *2.4.(b)* are scaled to form the normalized (dimensionless) constellation diagram in *Fig.2.4.(c)*, so as to represent efficiently the EVM. The S_I and S_Q axes are the real and imaginary axes derived and which compound the normalized constellation.

Ideal constellation diagrams

Ideal constellation diagrams show the ideal position of symbols for a given modulation type which are often represented by symbols at integer levels. Furthermore, the number of levels along either an in-phase or quadrature axis for an ideal constellation is

$$n = \sqrt{M} \tag{2.3}$$

For example, since M = 16 for 16-QAM, n = 4 for both the in-phase and quadrature axes. The integer coordinates of the ideal constellation points or each symbol are, **[29]**

$$C_{ideal,pq} = C_{I,ideal,pq} + j \cdot C_{Q,ideal,pq} = (2p-1-n) + j(2q-1-n) \tag{2.4}$$

where p and q are integers which satisfy $1 \le p \le n,\ 1 \le q \le n$.

By comparing the constellation diagram of the IQ measured time with the ideal constellation, several impairments such as IQ gain imbalance can be detected.

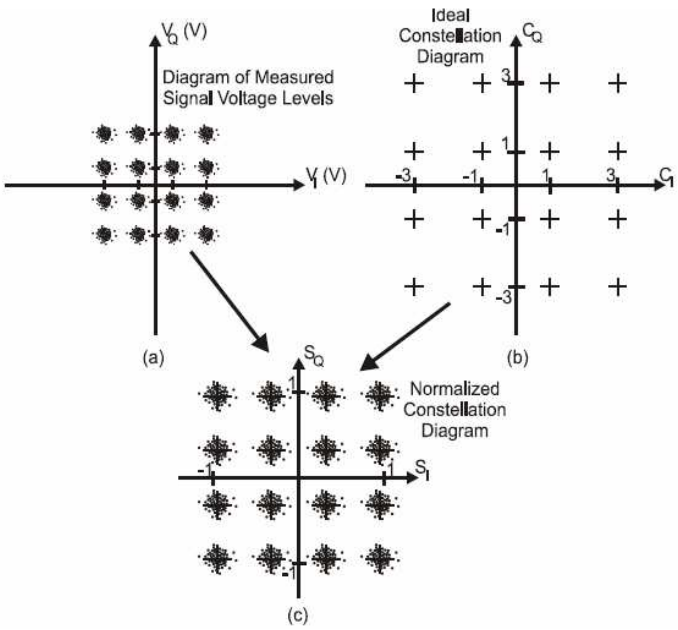


Fig.2.4. (a) Plot of the measured symbols, (b) Ideal constellation diagram, (c)A normalized constellation which facilitates calculation of EVM. **[29]**

A uniform distribution of the transmitted symbols into the constellation is assumed in order to carry out the normalization, translating into an equal probability of visiting each location of the symbols on the constellation.

As shown in *Fig.2.5.*, each symbol position or state in the constellation diagram represents a specific bit pattern (a coded symbol) and symbol time.

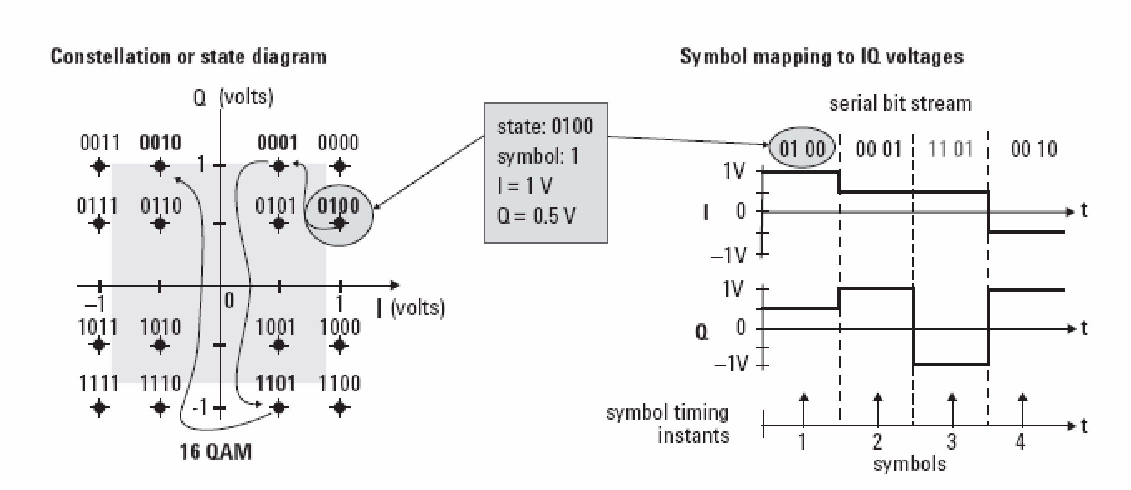


Fig.2.5. Constellation diagram and the correspondent I/Q waveforms **[30]**

2.2.2.2. Error Vector Magnitude (EVM) & Bit-Error-Rate (BER)

Error Vector Magnitude (EVM) measurements are often performed on VSAs, real-time analyzers or other instruments that capture a time record and internally perform a Fast Fourier Transform (FFT) to enable frequency domain analysis. Calculation of EVM is often accomplished through software internal to these instruments. Signals are down converted before carrying out EVM calculations **[29]**.

EVM is a common figure of merit for assessing the quality of digitally modulated telecommunication signals. As depicted in *Fig.2.6.,* EVM is an scalar which expresses the differences between the expected complex voltage value of a demodulated symbol (I-Q reference) and the value of the actual received symbol (I-Q measured).

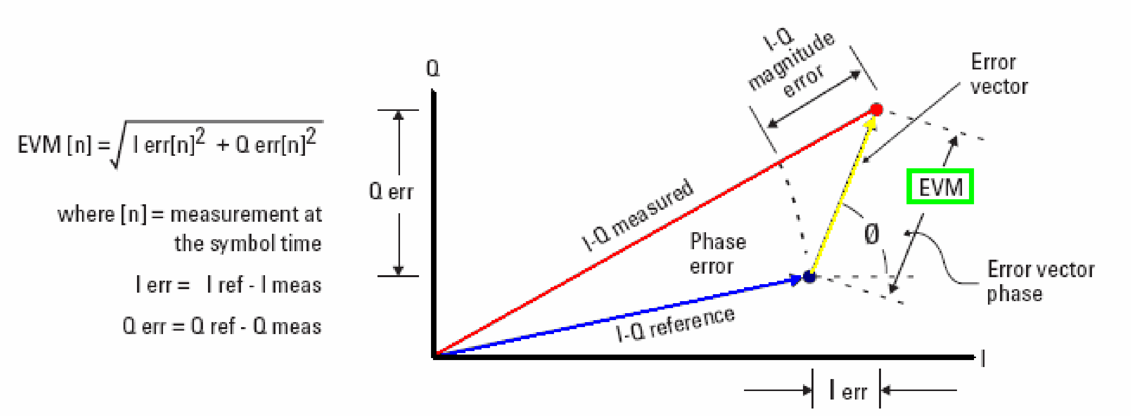


Fig.2.6. Graphical and vectorial representation of EVM

Mathematically, EVM can be defined as the root mean square (rms) of the error vector over time at the instants of the symbol clock transitions. By rule, EVM is usually normalized to the square root of the average symbol power and by convention, EVM is expressed as a percentage of the peak signal level in the constellation diagram.

The bit error rate (BER) is the most significant performance parameter of any digital communications system. It is a measure of the probability that any given bit will have been received in error.

The BER depends primarily on the signal to noise ratio (SNR) of the received signal which in turn is determined by the transmitted signal power, the attenuation of the link, the link dispersion and the receiver noise. Furthermore, measurement of the BER is not a trivial process and requires sophisticated and expensive equipment to achieve accuracy, particularly at high bit rates.

If a comparison between BER and EVM is set, it can be assured that BER gives a simple one-to-one binary decision as to whether a bit is erroneous or not, whereas EVM is more of a measurement of errors between the obtained symbols and expected symbols.

EVM measurements are sensitive to any signal impairment that affects the magnitude and phase trajectory of a signal for any digital modulation format, thus making it an ideal measurement tool for troubleshooting communications system problems at baseband, IF, or RF sections of the radio.

The BER as a function of the signal-to-noise ratio (SNR) for a M-QAM system, assuming that the noise affecting is additive white Gaussian noise, is based on the expression that follows **[31]**:

$$BER = \frac{2 \cdot \left(1 - \frac{1}{\sqrt{M}}\right) \cdot erfc\left(\sqrt{\frac{3 \cdot SNR}{2 \cdot (M-1)}}\right)}{\log_2 M} \tag{2.5}$$

Where the SNR is related to the EVM as shown below:

$$SNR = -20 \cdot \log \frac{EVM(\%rms)}{100} \tag{2.6}$$

Evaluating the expression (2.5) for a 16-QAM signal, the calculated BER is:

$$BER = \frac{3}{8} \cdot erfc\left(\sqrt{\frac{SNR}{10}}\right) \tag{2.7}$$

And this will be the expression used to calculate BER in these test setups.

The EVM trace in the VSA, the *error vector time data*, displays the EVM in the time domain, computing the EVM between corresponding symbol points in the I-Q measured and I-Q reference signals. By inspecting this trace, the errors occurred during the symbol transmission can be identified, since it can show whether errors occur at one or a few particular states or during the transition between them.

Detailed error measurements such an overall measure of EVM (%rms over all symbol detection/clock locations) is included in the error summary table, which also contains the demodulation bit stream and other error measurements.

2.2.2.3. Complex Spectrum Measurement Description

The power spectrum, also called frequency-domain representation of a signal, is defined as the range of frequencies that this signal spans from minimum to maximum, that is, a frequency-domain graph which shows how much of the signal lies within each given frequency band over a range of frequencies.

The VSA is fundamentally a digital system that uses DSP to perform spectrum analysis with FFTs (Fast Fourier Transform), and uses demodulator algorithms to perform vector-modulation analysis. The analog signal must be digitized in the time-domain, and then the FFT algorithm is executed and computes the spectra.

Conceptually, the VSA implementation is not complicated, since it is only needed to digitize the input signal and compute the measurement results.

Below is presented a block diagram of a simple transmission distance. Only the functions related to the transmitter and the receiver are considered, to be exact, the details about the VSG and VSA equipment.

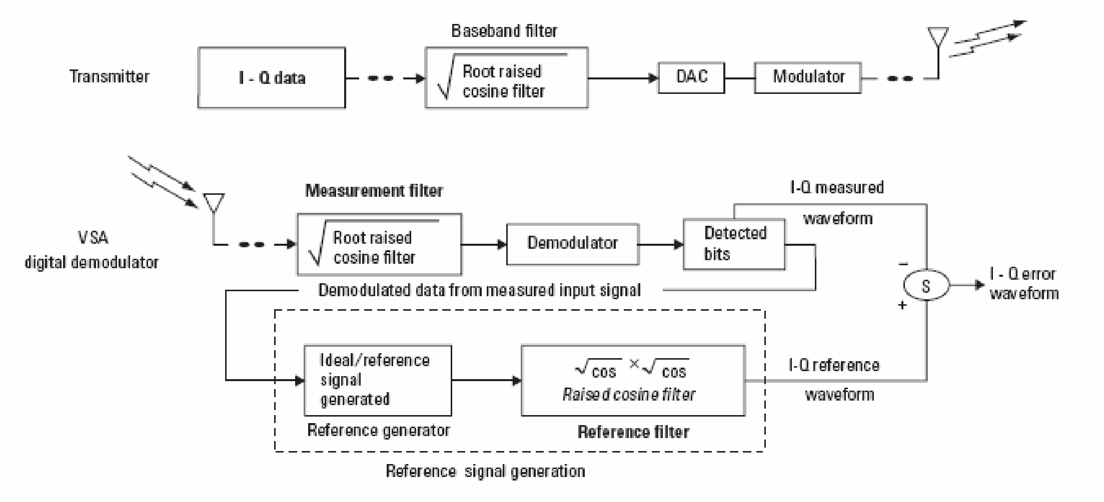


Fig.2.7 Block diagram of a complete transmission system

Concerning to the Spectrum trace provided by the VSA, it is important to adjust the two main parameters when analyzing and demodulating a signal: the *centre frequency* and the *frequency span* in the trace. The range, related to the amplitude of the signal, should be another parameter to take into account.

The spectrum for a 16-QAM signal is illustrated below:

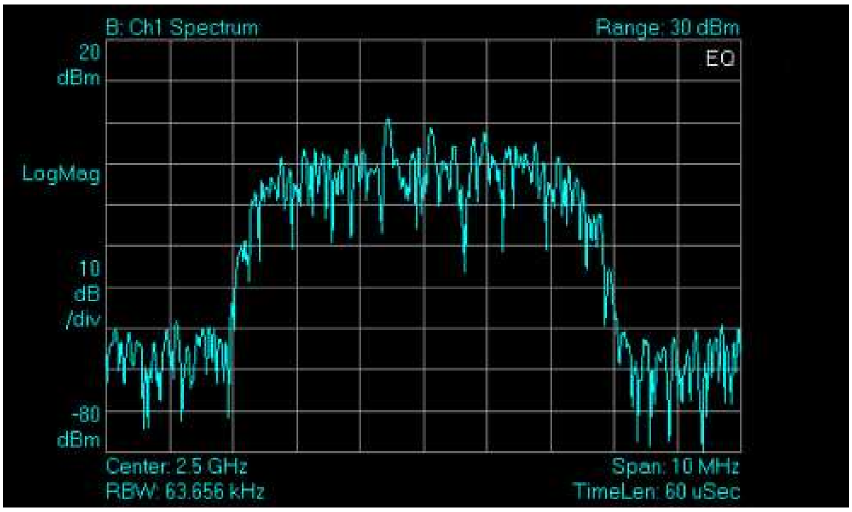


Fig.2.8. 16-QAM Spectrum

Chapter 3. Experimental Work

This chapter deals with the parameters, variables and procedures followed in order to carry out the three experiment setups, as well as the results obtained.

3.1. Generation of a waveform file (Matlab)

This section covers a brief description of the waveform file, a concise exposition of the procedure to create it and a justification of the chosen parameters in the system. The detailed description of the simulation program is provided in Appendix A.

In order to carry out the digital modulation and generate the waveform file, a program which simulates the 16-QAM transmission is created in Matlab.

Particularly, the program generates a 16 Quadrature Amplitude Modulated signal starting from a binary signal source, the symbols are converted into Gray code, and employing the Matlab qammod function the 16-QAM constellation is obtained. Subsequently, filtering is applied by means of a RRC filter, and passed through an AWGN channel of SNR equal to 20 dB, before extracting the I and Q components. The waveform file is created while interleaving I and Q signals, and it is saved in the VSG format and loaded into a Matlab array before being downloaded on to the VSG.

Initial parameters

```
% PARAMETERS DEFINITION
M = 16;                          % Size of signal constellation
k = log2(M);                     % Number of bits per symbol
points = 12500;                  % Number of points per bit
nsamp = 4;                       % Upsampling rate
```

In the previous piece of code, the initial parameters of the waveform file are set. The number of points per bit simulates the number of points that will be used to create the random data that compose the input binary stream.

The variables "M" and "k" are the known values for a 16-QAM constellation, the number of levels and the number of bits that a symbol is made of in this modulation format. The upsampling factor is set to 4, a value that will be used in the filter design and will be clarified later in a different subsection

Signal source

```
%% SIGNAL SOURCE
data = randint(points,1);        % Random binary data stream
preamble = [0 0 0 0 0 0 0 1 0 0 1 0 0 0 1 1 0 1 0 0 0 1 0 1 0 1
1 0 0 1 1 1 1 0 0 0 1 0 0 1 1 0 1 0 1 0 1 1 1 1 0 0 1 1 0 1 1 1
1 0 1 1 1 1].';                  % Preamble sequence of 64 bits
burst = [preamble;data];
```

This piece of script creates a binary data stream, which includes a random data sequence (data), and a known sequence of fixed binary bits called "preamble", to ensure that all the symbols will be demodulated, because it contains all the symbols of a 16-QAM constellation. The "burst" vector is the concatenation of the previous ones, and symbolizes the data stream which will be filtered and sent to the channel.

Modulation

The commands below create the 16-QAM modulation and get the constellation values.

The qammod function is applied to a vector of integers between 0 and 15, resulting in an output vector containing all points in the 16-QAM signal constellation, presented subsequently.

```
%% MODULATION
y = qammod(xsym,M);
% Plot the transmitted constellation before adding noise and
% filtering the signal
scatterplot(y); title('QAM Scatter Plot before filtering')
```

The simulated initial constellation, before applying pulse-shaping and before be sent to the AWGN channel is depicted below.

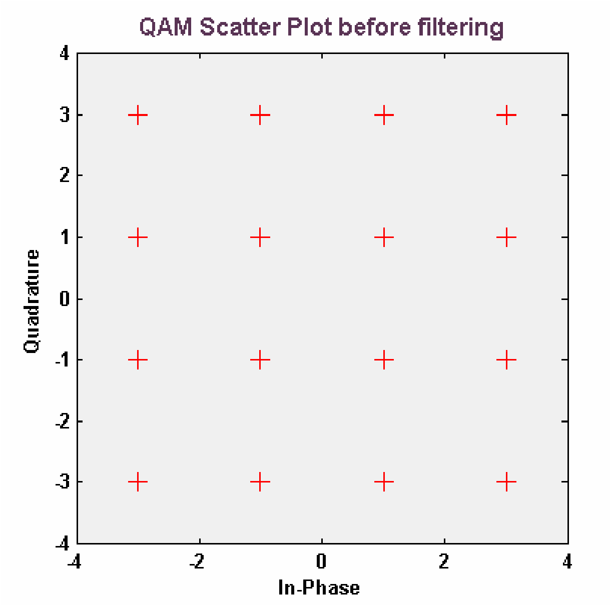


Fig. 3.1.Constellation diagram for the 16-QAM before filtering and passed through the AWGN channel

Filter Design

The way to implement the transmission filter is described in the piece of code below:

```
%% FILTERING. Filter the I and Q signals, using
% raised cosine filters (RRC filters)
```

```
%% Filter Definition. Define filter-related parameters.
Rolloff = 0.5;                 % Rolloff factor of filter
filtorder = 80;                % Filter order
delay = filtorder/(nsamp*2);   % Group delay (#of input samples)

% Create a square root raised cosine filter.
Rrcfilter = rcosine(1,nsamp,'fir/sqrt',rolloff,delay);
```

The Root-raised cosine filter converts symbols to baseband waveforms to be transmitted over the channel. It is assumed to use RRC filtering in the transmission unit because, as explained in ***chapter 1***, it has to be combined with the matched RRC filter in the receiver to meet Nyquist's criterion for zero ISI and result in a raised cosine filter response for the whole system.

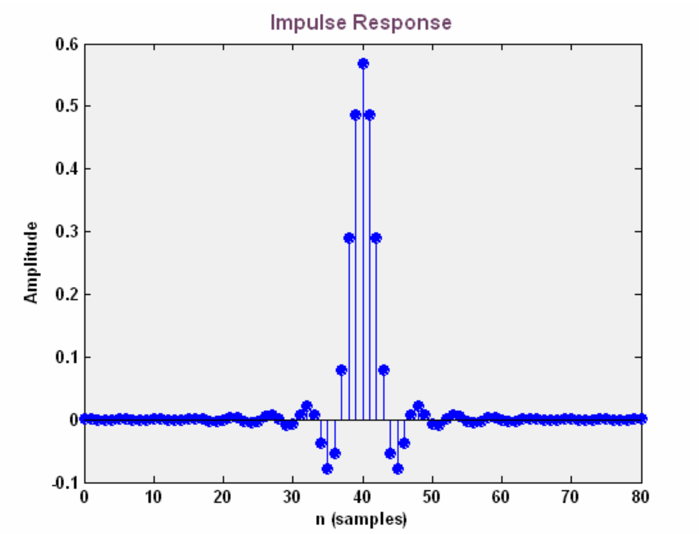


Fig.3.2.Plot of the impulse response of the raised cosine filter

Shown here are the eye diagrams for the in-phase and quadrature root raised cosine filtered components of the 16-QAM signal before being injected into the AWGN channel. The eye diagram is a convenient visual method of diagnosing problems with data systems.

This tool shows clearly the "eyes" between the discrete states, and illustrates how critical the sample timing must be to detect the symbol at the maximum eye opening. The eye opening for a 16-QAM system is so much narrower and the spacing between decision boundaries so much smaller than those in the 4-QAM case, for instance, and it gets progressively worse as the number of symbol states rises.

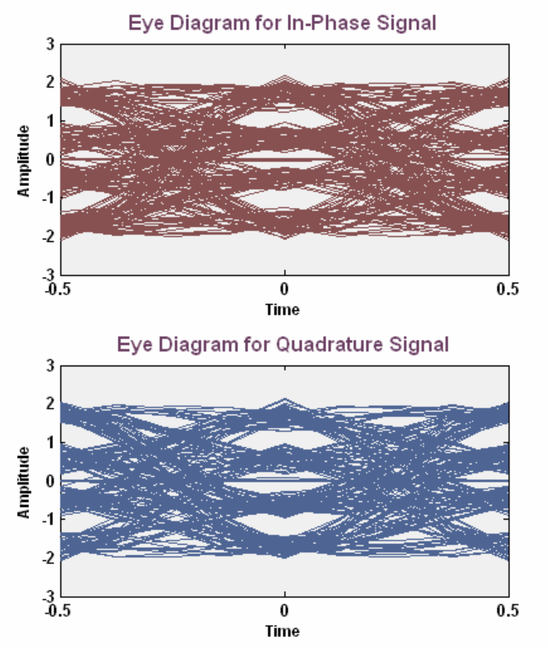


Fig.3.3.Eye diagram for the in-phase and quadrature signals before being injected into the AWGN channel

Choosing the roll-off factor

By examining the equation (1.7), for an alpha of 0.5, the transmitted bandwidth decreases from 2 times the symbol rate (when $\alpha = 1$) to 1.5 times the symbol rate. This results in a improvement in the occupied bandwidth. The smaller alpha takes more peak power because of the overshoot in the filter's step response. This produces trajectories which loop beyond the outer limits of the constellation.

Choosing the right upsampling ratio and the length filter

Concerning to the filter design with Matlab, both issues are related. To obtain the proper performance and meet the specifications, choosing a reasonable filter length with a practical upsampling ratio would be expected:

- Ideally, the design would require exhibiting a high upsampling ratio, which would lead to a faster DAC speed; but it would be limited by practical considerations, since it would involve an increase in the hardware complexity. A typical upsampling ratio is 4 times the symbol rate, value which should enable the designer to achieve adequate aliasing rejection with a reasonable filter length.
- As mentioned, longer the filter length, better the rejection of aliases. Nevertheless, more taps means higher hardware complexity, which means a trade-off between filter length and complexity to be reached. Finally, the chosen value for the filter order is set to 80, thus obtaining a delay of 10 samples.

AWGN Channel

```
%% CHANNEL. Transmit signal through an Additive White Gaussian
% Noise channel

EbNo = 20;                                         % Eb/No in dB
snr = EbNo + 10*log10(k) - 10*log10(nsamp);        % SNR in dB
noisy_qam = awgn(y_tx,snr,'measured');
```

The parameter EbNo denotes the ratio between the average energy per bit (Eb) and the noise power (No). Since SNR performance is better for higher values of EbNo, it was set to 20 dB. This value was chosen after performing the experiment with other EbNo values of 15 dB and 25 dB.

Fig.3.4. shows a simulation of the I and Q waveforms obtained after filtering, that is, the transmitted I and Q waves which will be downloaded onto the VSG.

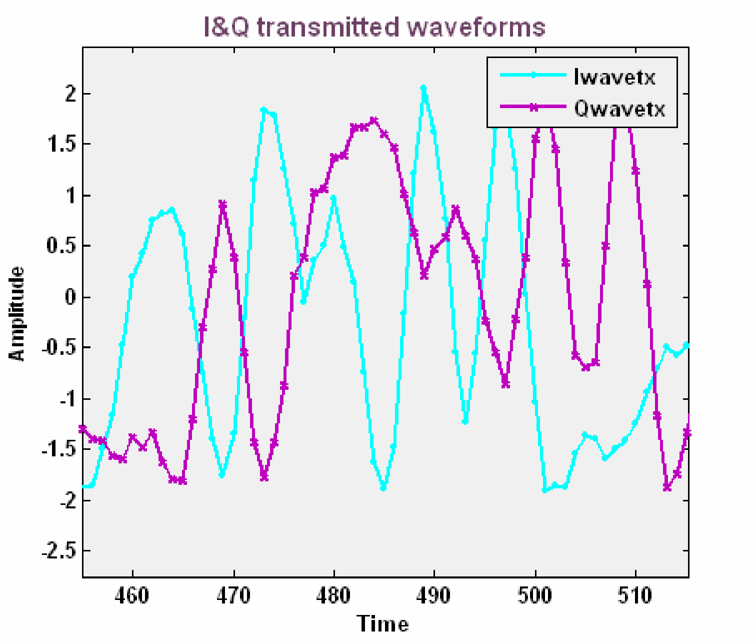


Fig.3.4. Time-domain representation of the transmitted I and Q waveforms

Choosing the right symbol rate

This issue deserves a whole section to be discussed, because it was one of the major difficulties to overcome when describing the system, owing to the lack of information about it and its strong relationship with the modulator and demodulator.

Concerning to the signal information, the choice of a right symbol rate is critical before performing the experiment setup, because specifying an incorrect symbol rate introduces errors in the demodulation process, thus being unable to receive the right signal.

Definition

The symbol rate, also known as baud rate or modulation rate, is defined as the number of distinct symbol variations (signalling events) made to the transmission medium per second in a digitally modulated signal or a line code **[32]**. In other words, it is a parameter that determines the rate or frequency at which symbols occur, where the symbols, as mentioned before, consist of 4 bits in a 16-QAM signal.

Symbols are valid only at the timing instants when the receiver interprets the signal, the so-called detection-decision points; since the analyzer's demodulator uses the symbol rate to determine the frequency of these points. Accordingly, setting the symbol rate in the VSA to match exactly the symbol rate of the system is essential and therefore, a trade-off between some of VSA and VSG factors must be considered:

- On the one hand, since the signal is created from Matlab and then downloaded onto the Agilent VSG, the symbol rate of the system is directly proportional to the ***reconstruction clock*** on this piece of equipment (also called sampling frequency).

- On the other hand, referring to the analyzer restrictions, a parameter that must be taken into account is the selected ***frequency span***, since the symbol rate determines the maximum frequency span (or information bandwidth) that one can measure.

As mentioned in VSG specifications (**section 2.1)**, the sampling frequency can be adjusted between a minimum value of 1 kHz and a maximum value of 125 MHz. The default value when the instrument is launched is 125 MHz.

The maximum frequency span or information bandwidth which allows representing the whole signal in the spectrum trace provided by the VSA mode is 10 MHz. By choosing this value, it is observed that all of the signal's energy falls within the span, thus accomplishing the requirements. Furthermore, the minimum frequency span is closely related to the symbol rate, as demonstrated in equation (1.7).

The formula, valid for PSK and QAM signals that use raised cosine or root-raised cosine filtering at the transmitter, indicates that when selecting a span that is too narrow, the measurement may have excessive errors or the analyzer may lose carrier lock.

After taking into consideration these issues, the sampling frequency was set to 16 MHz, with a frequency span or information bandwidth of 10 MHz and a roll-off factor equal to 0.5. Assuming the upsampling factor to be 4 (given in the Matlab code), so as to calculate the symbol rate of the system, the following equation was applied:

$$Symbol\ rate = \frac{Sampling\ frequency\ VSG}{number\ of\ \ points\ per\ symbol} = \frac{f_{CLK}}{n} \qquad (3.1)$$

As a result, the highest achievable symbol rate of the system was chosen to be 4 MHz, that is, 4 Msymbols/sec, which is equivalent to a bit rate of 16 Mbits/sec. When selecting a frequency span of 10 MHz, slightly larger than the signal bandwidth, all the signal components were included, and the measurement was pretty accurate.

3.2. Experiment setups

This section covers the experimental link designs, parameter settings and the results obtained in each configuration, in addition to graphs and figures representing the signals involved, their spectrum and other measurements.

Ideally, in optical communication systems, it is desired to transmit a signal for long lengths of fibre, at high bit rates (more information per second) and receive it without errors. In practice, the upper limits of transmission length and bit rate are a result of the possibility of an unacceptable number of errors in the received signal. The most common maximum BER is of 10^{-9}, which means one error is tolerated in 10^{9} bits sent, but in these tests, as will be explained, this limit will be set to a BER of 10^{-8} for the 16-QAM transmission.

Understanding the origin of such errors is essential in order to be able to reduce them and improve the performance of the system, and such task will be performed with the EVM measurement.

The complete system setup considered is depicted in the block diagram below:

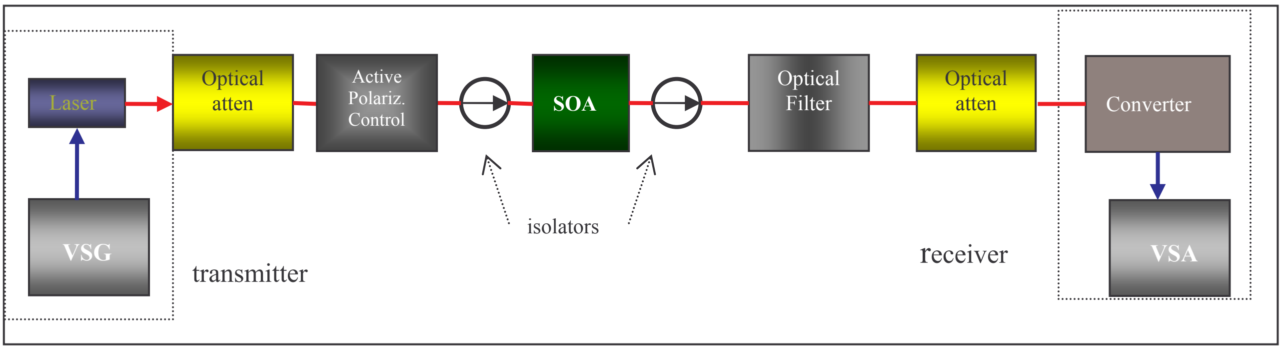


Fig.3.5. Schematic of the experimental system arrangement

At the input, a **VSG** (Agilent Tech.) is employed as a signal source and generates a 16 Mb/s Quadrature Amplitude modulated signal, modulating a laser diode at 2.5 GHz. The Distributed Feedback (DFB) **laser** (HP 83403-C), made from InGaAs, possesses an emitting wavelength of 1547.0 nm in the modulation range of 300 kHz to 6 GHz, and gives a fibre-coupled power of approximately 4 dBm (2.5 mW), also called average optical power. This emission wavelength corresponds to the minimum attenuation region of standard single-mode optical fibre.

The laser is supposed to have a very high linearity in terms of *spurious-free dynamic range* (SFDR) in order to guarantee excellent performance for most analogue applications. This magnitude is defined as the RF input signal power range in which the received signal can be detected in the presence of noise and amplified without nonlinear distortion. Nevertheless, in order to determine this value and recognize the suitability of the devices for these kinds of applications, a two-tone measurement should be performed, but neither the equipment nor the installed options in the VSG allowed performing this measurement (to know more about SFDR and the procedure used to measure it, see the references: **[33-36]**).

Another transmitter setting, the *modulation depth*, expressed as a ratio of the maximum information signal (modulation amplitude) to the amplitude of the carrier (mean value) in an amplitude-modulated signal, and considering a carrier amplitude of 10 dBm, has a value of 0.36 (36 %).

This quantity is high enough to represent the 2.5 GHz sine wave as a clean signal and without distortion or intermodulation products.

The emitted light from the lightwave source is leaded into an optical **attenuator** used to model the fibre link loss, and then, depending on the configuration, amplified by a **SOA block** (Kamelian Ltd). Placed before the SOA, there is a **polarization controller** used to reduce the reflection-induced laser intensity noise, and an optical **isolator**. In a practical system, the polarization varies along the fibre length, so an isolator is a good alternative for avoiding multiple reflections.

The SOA features a 1550 nm amplification window with a gain of approximately 24 dB (23.88 dB for optical input powers lower than -25 dBm and a forward current of 270 mA). The SOA noise figure to a forward current in the range of 200 – 250 mA and 1550 nm is approximately 6 dB.

Another isolator is inserted between the SOA and the **narrowband optical filter** (Santec) centred in a 1547 nm wavelength. The filter, with a 3dB bandwidth of 0.49 nm placed before the receiver, minimizes the amplified spontaneous emission (ASE) noise generated by the SOA, eliminating the out-of-band noise. The optical receiver (Agilent), a **lightwave converter** centred in the 1200 – 1600 nm window, and a maximum input power of 10 mw, is used to collect the signal and its output is connected to the **VSA**, where the constellation and I/Q diagrams, the spectrum and other measurements are displayed.

In all the measurements, the variable attenuator loss will be increased until the EVM exceeds the limit of 8% set for 16-QAM transmission, which is equivalent to a BER of less than 10^{-8} and then use the following equation,

$$L = \frac{Atten[dB]}{0.25\left[{}^{dB}\!/\!_{km}\right]} \tag{3.2}$$

to compute the expected length of the fibre span.

In the previous equation, *Atten* indicates the attenuator value which corresponds to the EVM limit, and 0.25 dB/km is the ratio between fibre loss and distance in km.

Fig.3.6 shows the entire experiment setup in the Optical Communications Laboratory, including the name of all the components of the system

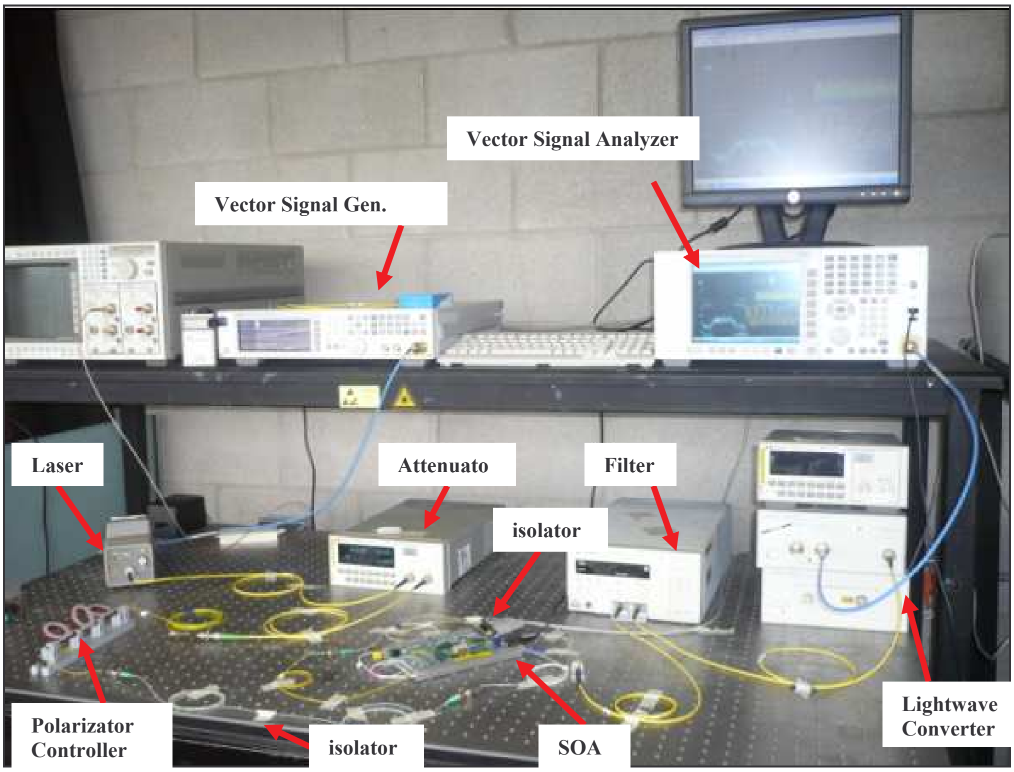


Fig.3.6. Experiment setup in the Optical Communications Laboratory

3.2.1. Back-to-back configuration

Back-to-back configuration is the experiment setup which involves the direct connection of the transmitter to the receiver without considering active devices, (SOA excluded) except for the attenuator, the unique irreplaceable element which simulates the path losses, and so including the effect of the transmission link.

The tests consist of varying the attenuation, by increasing the attenuator value, and perform the EVM measurement with the VSA.

In this setup, the main goal is to evaluate this magnitude without optical active elements in the link arrangement and characterize the link length, by means of the relationship between the attenuation in dB/km in a silica optical fibre and the wavelength (*Fig.1.7.*). The schematic of the experimental system arrangement is shown in *Fig.3.7.*

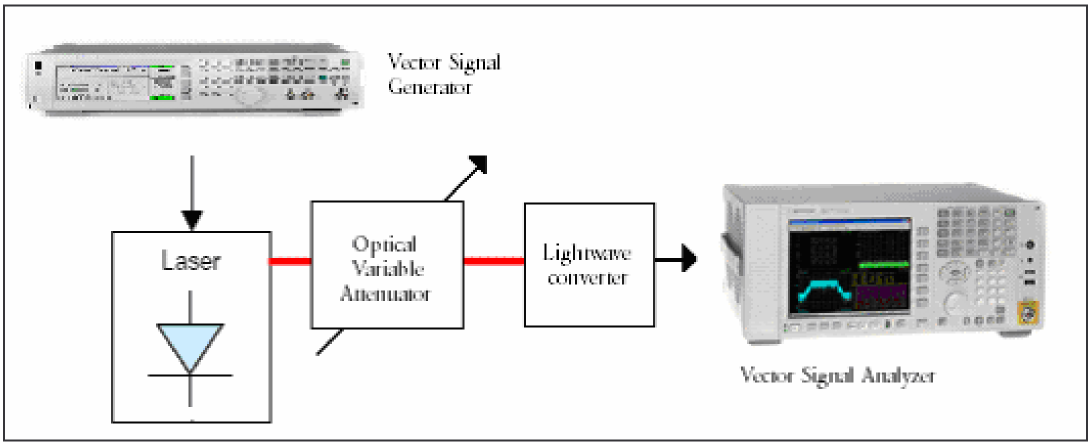


Fig.3.7. System scheme performed to characterize the link, with the attenuator.

Transmitter Settings

The transmitter component in a system must accomplish two functions. First, it must be a source of the light launched into the fibre-optic cable. Second, it must modulate this light to represent the binary data that it receives from the source.

The transmitter in this system is completed by the VSG and the laser devices. As stated before, the RF output from the VSG modulates the laser, with the 16-QAM signal generated in Matlab code. The parameter values are presented next.

a. 16-QAM Signal Parameters:

The table presented in next page exhibits the parameter values set in the code created in Matlab, for the 16-QAM waveform.

Some of the variables are adjusted whereas others are given by Matlab when the program code is executed. Their description is provided in **section 3.1.**

Table 3.1. Parameters of the 16-QAM signal

Variable	Value
Number of points input binary source (burst)	12564 (12500 data + 64 preamble)
Upsampling rate (nsamp in bits/symbol)	4
Transmitted symbols (xymb)	3141
Roll-of factor	0,5
Filter order (samples of the filter)	80
Filter delay (samples)	10
Channel SNR	20 dB
I and Q waveforms points	12644
Waveform points	25288

b. VSG Parameters

Table 3.2. Parameters of the VSG

Variable	Value
Sampling frequency	16 MHz
Runtime scaling	99%
Carrier Frequency	2,5 GHz
Carrier Amplitude	+ 10 dBm

c. Laser Specifications

Table 3.3. Laser Specifications	
Variable	Value
Operating wavelength	1.550 nm (1.547 nm)
Average Power	+ 4 dBm
Modulation depth	36% (0,36)

Receiver Settings

d. Lightwave Converter Parameters

Table 3.4. Lightwave converter specifications	
Variable	Value
Wavelength range	1200 nm to 1600 nm
Conversion gain (dc responsivity)	300 V/W
input optical reflection	0.05%
Bandwidth (characteristic)	dc to 15 GHz (optical) dc to 11 GHz (electrical)
Output Electrical Return Loss 0.1 to 12 GHz (characteristic) 12 GHz to 22 GHz	*> 11 dB** *> 9 dB**

* Refers to electrical power units

e. VSA Parameters

Table 3.5. Parameters of the VSA

Variable	Value
Digital Demodulator	16 QAM
Centre frequency	2.5 GHz
BW SPAN frequency	10 MHz (MAX)
Range	-6 dBm
Symbol Rate	4 MHz
Points/symbol	5
Result length (number of symbols demodulated)	500
Measurement Filter	Root Raised Cosine
Reference Filter	Raised Cosine
Filter Roll-off Factor	0,5

At a minimum, the demodulator requires the *modulation format*, the *symbol rate*, the *baseband filter type*, and *filter alpha*. This set of parameters is generally sufficient for the demodulator to lock to the signal and recover the symbols.

With a frequency SPAN of 10 MHz (the maximum), the spectrum occupied a 60% of the trace, appearing elevated above the noise floor a quantity of around 20 dB, as expected. The number of points/symbols was chosen high in order to see more detail of the Intersymbol waveforms. The *Meas Filter* represents baseband filtering in the system receiver and the *Ref Filter* represents baseband filtering in the entire system (total receiver and transmitter channel filtering).

Procedure

1. Connect the devices as shown in *fig.3.7.*
2. Run the program “16QAM_final.m” in Matlab. The created IQ waveform file is called “noisy3_QAM_EsgTestFile”.
3. Download the waveform file onto the VSG.

4. Set the parameters as shown in *table 3.2.* and modulate the carrier ("Mod On")
5. Set the attenuator value (set the link length). Start by zero. Push "Enable"
6. Turn on the laser and collect the signal.
7. Set the VSA parameters with the values shown in *Table 3.5.*
8. See the constellation diagram and the spectrum, and analyze the EVM and the summary errors table.
9. Increase the attenuator value in 1 dB
10. Repeat the steps 6 to 9 until an attenuator value high enough to observe the received signal without impairments or the constellation gets lost.

The obtained measurements and graphs, as well as the discussion of results, are presented in **section 3.3**.

3.2.2. SOA configurations

3.2.2.1. SOA as an optical preamplifier

As mentioned in **section 1.2.3**., the utility of this SOA configuration is to improve the receiver sensitivity. In this setup, the parameter settings are set identical to the ones provided in the back-to-back configuration scenery (see *tables 3.1 to 3.5*), with the difference that the optical active devices are at this time included. The transmitter includes the lightwave source modulated by the 16-QAM generated in the VSG, but the receiver consists of an optical preamplifier with two isolators on either side of the SOA, a narrowband optical filter and a lightwave converter, previous to the VSA.

The aim of this arrangement is to evaluate the significant variations in the system, in terms of the EVM in %rms and the constellation diagram, versus the attenuator value. The SOA, as mentioned before, provides a fibre-to-fibre gain of approximately 24 dB for a wavelength of 1.550 nm and maximum optical powers of -25 dBm at the input. The full description of the device is given in Appendix C.

The experimental system is depicted in the figure below:

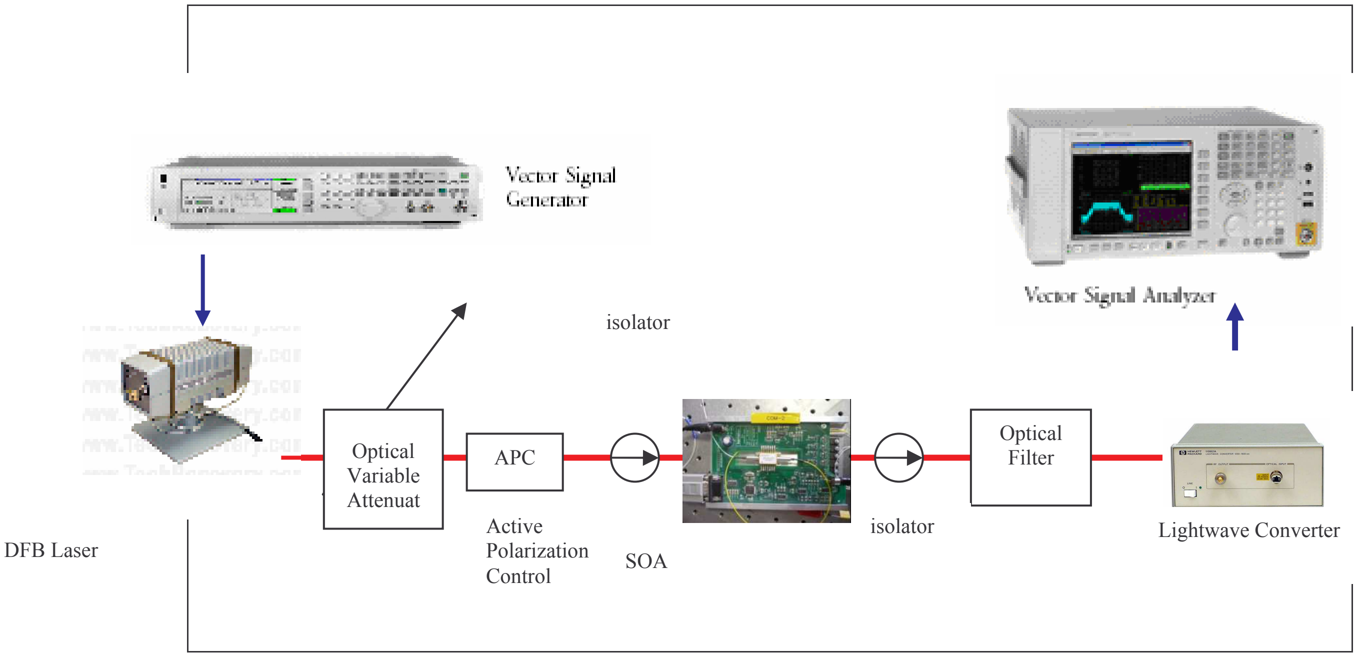


Fig.3.8. System scheme performed to characterize the link, with the SOA.

Before setting up the arrangement, the insertion losses of the involved devices where measured. The optical attenuator and the filter had insertion losses of 3 dB and 5.5 dB, respectively.

The procedure to follow in this case is the same as in the previous configuration, but with the difference in the connections. The attenuator variations are in steps of 2 dB, the forward current of the SOA is adjusted to 250 mA (high enough to perform good quality measurements), and the optical filter is adjusted to a 1547 nm wavelength before executing peak searching.

After repeating the measurements several times, the spectrum range in the VSA display was also set to -6 dBm, being able to perform great measurements up to 40 dB of attenuation.

3.2.2.2. SOA as an in-line amplifier

The schematic system setup is presented in *Fig.3.9.,* preserving the previous configuration with the addition of a second attenuator, placed before the receiver. The main goal of this setup is to study the SOA block as a device used to compensate for fibre and other transmission losses in medium and long-haul links. In this case, the value of the first attenuator is set to a constant value equal to the SOA gain, with the intention to study the effect of the SOA and second attenuator in the haul. As previously mentioned, the SOA gain for a wavelength of 1550 nm is 24 dB, so the first attenuator is set to a constant value equal to the SOA gain and the second attenuator is the adjustable variable.

The complete system setup considered is shown in the figure below:

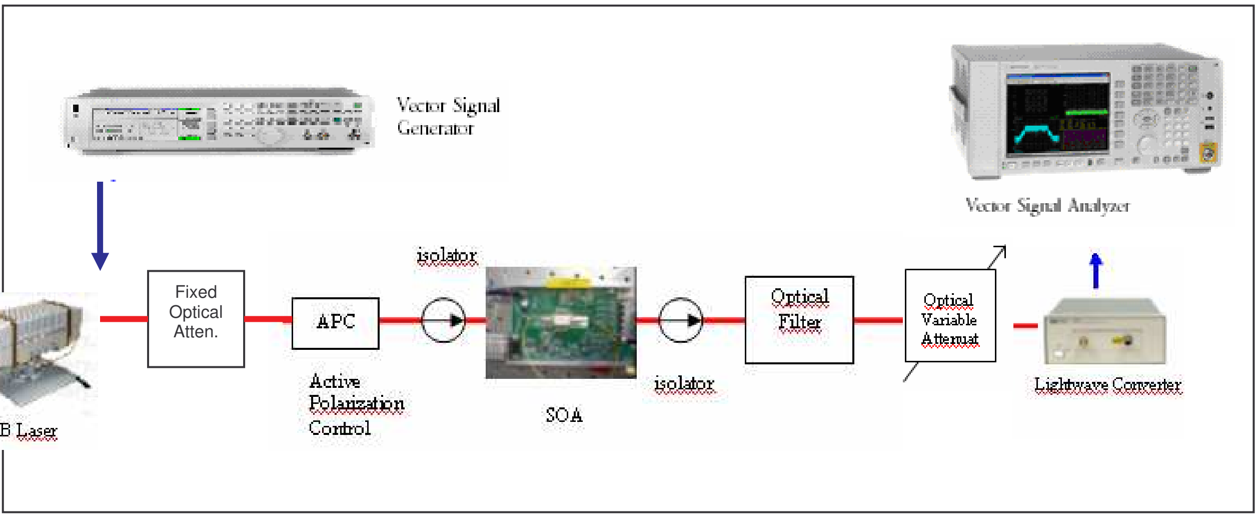


Fig.3.9. Schematic of the setup considering the SOA as an in-line amplifier

The insertion losses measured for the second attenuator were of 2.4 dB approximately.

As mentioned, the procedure follows the same modus operandi that the previous one, but with the difference that the first attenuator is adjusted to a fixed value and the second attenuator is variable, in steps of 1 dB.

3.4. Discussion of results

Back to back configuration

The complete table of results is provided in Appendix B. According to the EVM limit of 8% set for 16-QAM transmission in this experiment, a distance of approximately 100 km can be reached without any SOA block (corresponding to 25 dB of attenuation loss).

The achievable optical power in this case results to be around -23 dBm, corresponding to an EVM of 7% and a SNR around 22 dB.

Error free transmission, which corresponds to a BER less than 10^{-15}, is achieved until a transmission length of 92 km, which corresponds to a 23 dB of attenuation loss and an EVM of 5.74 %rms.

Below are presented different figures of the demodulated data with the VSA main traces, for different values of attenuation, in order to analyze the differences in the IQ diagram, the spectrum and the constellation.

<u>- Attenuation loss = 5 dB:</u>

Judging by results given in *Fig.3.10* lead to the following conclusions:

As expected, for low attenuation losses (short transmission distances), the IQ diagram is presented pretty clear, without meaningful impairments or gain imbalances or phase noise. All the demodulated symbols are set in the right location of a 16-QAM signal, as well as the state transitions.

The spectrum measurement is also accurate, with a noise floor of -65 dBm and a peak power of around -40 dBm, showing the shape of a raised-cosine filter, as predicted.

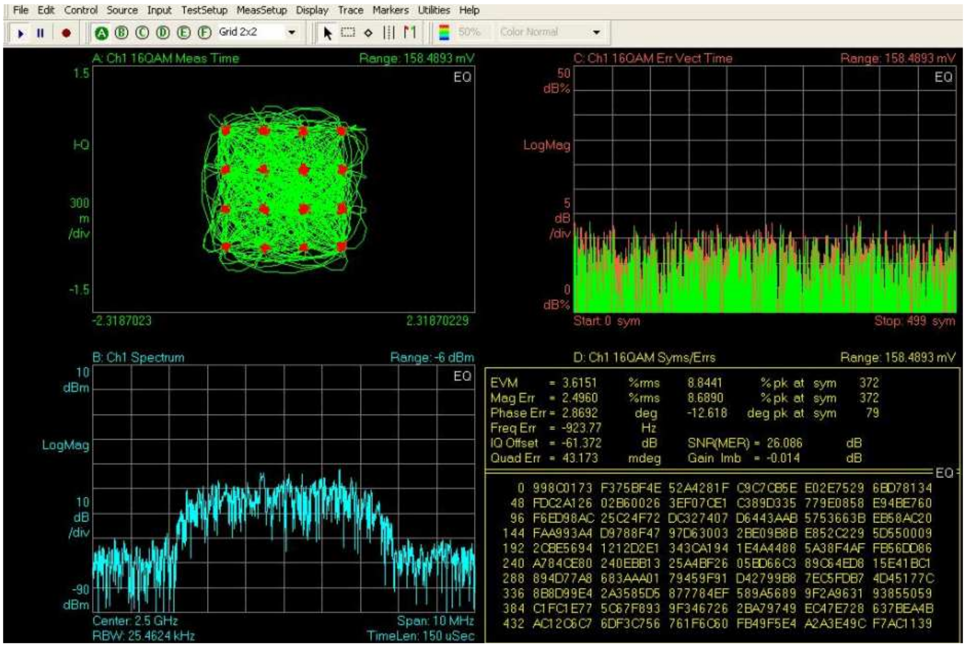


Fig.3.10.VSA results for an attenuation loss of 5 dB

The EVM trace presents a flat response, suggesting that errors between adjacent symbols are meaningless and without no error with the choice of the symbol rate. The EVM [%rms] value considering all the demodulated symbols is around 3.6%, which denotes a good quality of the transmission.

<u>- Attenuation loss = 15 dB:</u>

In this case, the more significant difference in comparison to the previous figure is given by the spectrum, although the constellation is slightly spreader. There are no meaningful changes between the EVM values.

When exploring the error summary table, it can be affirmed that none of the error magnitudes presented show important variations.

When increasing the attenuation loss, no difference is noticeable until 20 dB, the point where the constellation starts to spread and the spectrum is unrecognizable.

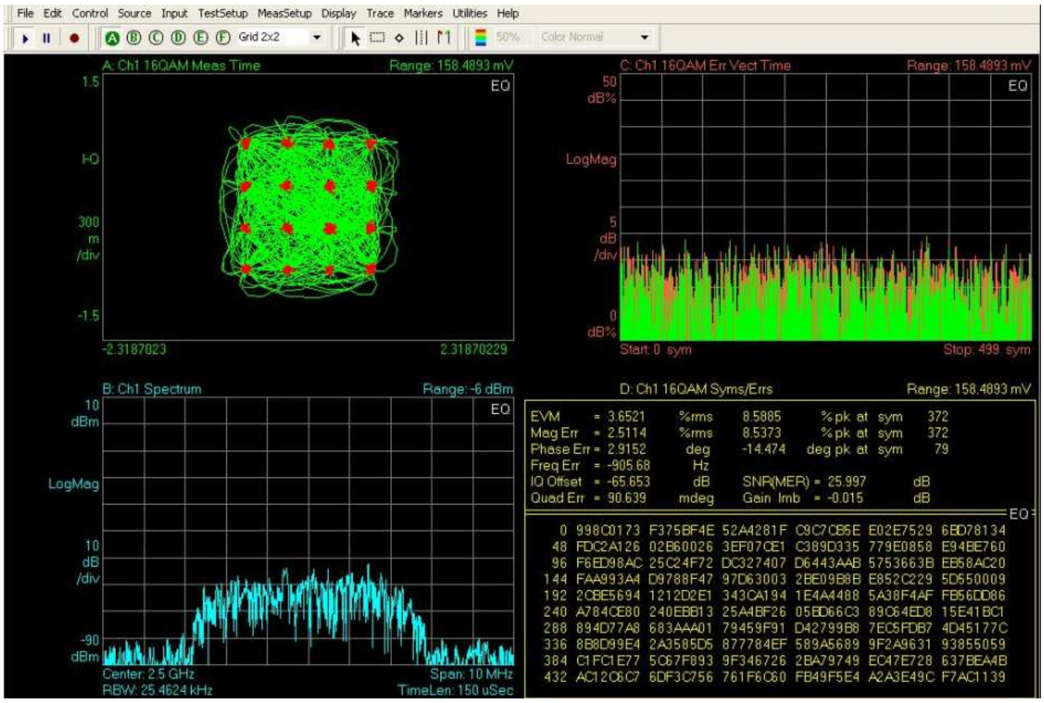


Fig.3.11. VSA results for an attenuation loss of 15 dB

<u>- Attenuation loss = 25 dB:</u>

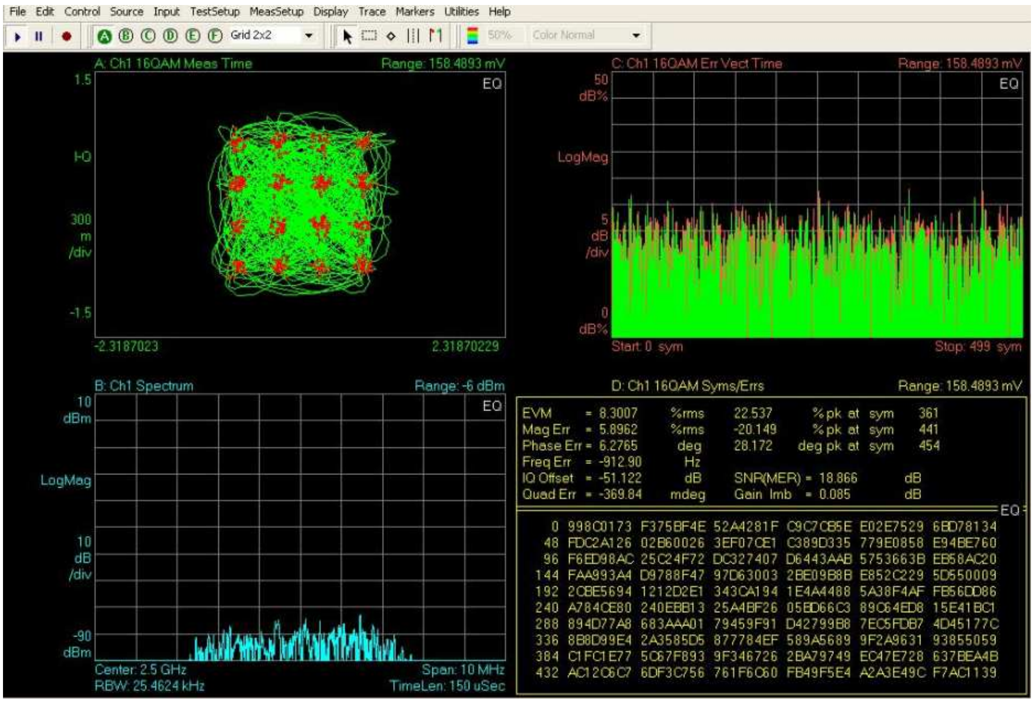


Fig.3.12. VSA results for an attenuation loss of 25 dB

Once reaching this value, the constellation shows expanded symbols and the spectrum becomes almost invisible. The EVM is slightly superior than the fixed limit for a good-quality transmission, and the magnitude errors shown in the summary table, specially the Magnitude Error and the Phase Error have augmented and now their value are twice the value when the attenuation loss was 5 dB.

To mathematically evaluate the link performance for the back-to-back configuration, plots of the EVM [%rms] and BER of the received signal against the attenuation loss are depicted in the below. As expected, the EVM grows when the attenuation loss (or link length) increases, with slightly variations, with a minimum EVM of 3.6% a transmission distance of 100 km and an abrupt boost from this value.

The same occurs with the BER, but in this graph the values less than 10^{-12} have been rejected, since low attenuation losses corresponded to very slow values of BER, unrealizable in practice. They have been considered meaningless. As mentioned before, a good performance of the system is given by values of attenuation up to 25 dBs approximately, corresponding to a BER of 10^{-8}.

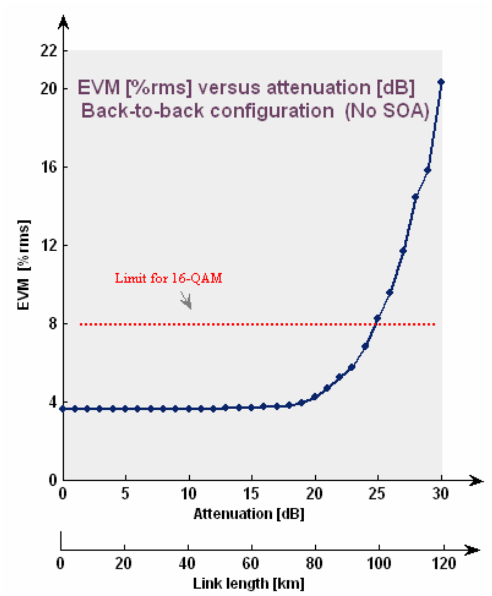


Fig.3.13. EVM vs. attenuation loss (back-to-back)

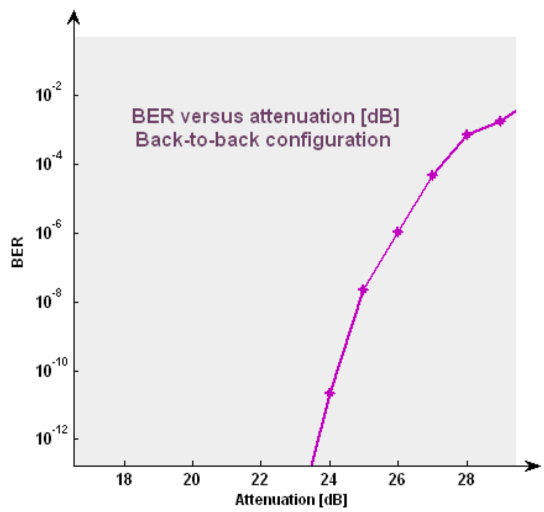


Fig.3.14. BER vs. attenuation loss (back-to-back)

Furthermore, observing the experimental results in table 1 (Appendix B), it is demonstrated that, as the span length increases, the optical power at the receiver decreases, as it was expected. As the signal propagates down the length of fibre it suffers power loss due to attenuation, and hence a decreased SNR.

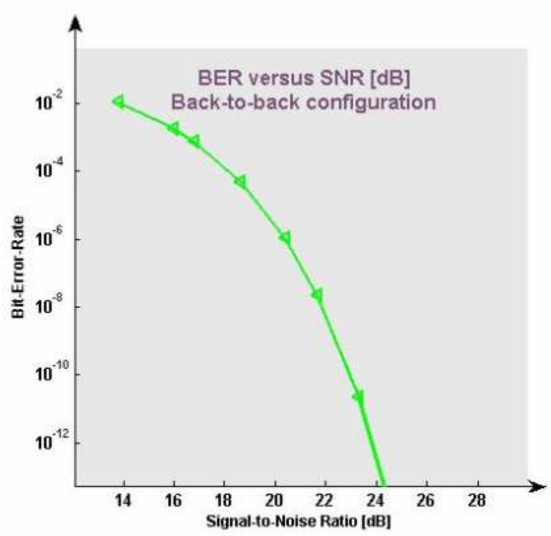


Fig.3.15. BER vs. SNR (back-to-back)

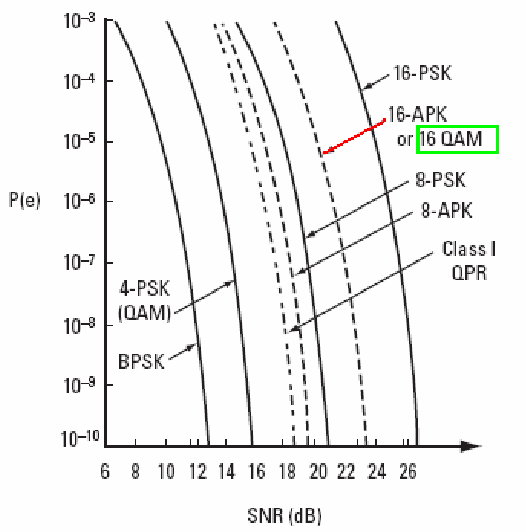


Fig.3.16. Theoretical curve BER vs. SNR **[38]**

Clearly it can be seen in *Fig.3.15*, an increase in signal to noise ratio (SNR) would decrease BER. If we have greater SNRs, the signal level relative to the noise is higher, and hence the probability of error is reduced. *Fig.3.16.* shows the theoretical curve of error probability versus SNR in dB. As shown, the plot on the measured BER (3.15), calculated with the equation (2.7), almost coincides with the theoretical curve given on the right.

Optical preamplifier configuration

Experimental results given in *Fig.3.20,* demonstrate that with one SOA block, the 16-QAM signal for this experiment can be transmitted over approximately 144 km of SMF with BER smaller than the limit (equivalent to 33 dB of fibre loss).

In this case, the achievable optical power results to be approximately -22 dB, only 1 dB loss of difference respecting to the optical power measured in the back-to-back case; and a SNR nearly to 23 dB.

Error free transmission, corresponding to BER values less than 10^{-15}, is achieved until a transmission length of 132 km, which corresponds to a 33 dB of attenuation loss and an EVM value of around 5.9 %rms.

It can be seen that the insertion of the SOA block extends the achievable link length by approximately 40 km but also slightly degrades slightly EVM performance.

Indeed, the maximum increase in EVM relative to the optical back-to-back case is about 0.8% for the 16-QAM signal.

Below are presented different pictures of the demodulated data, corresponding to different values of attenuation.

<u>- Attenuation loss = 6 dB:</u>

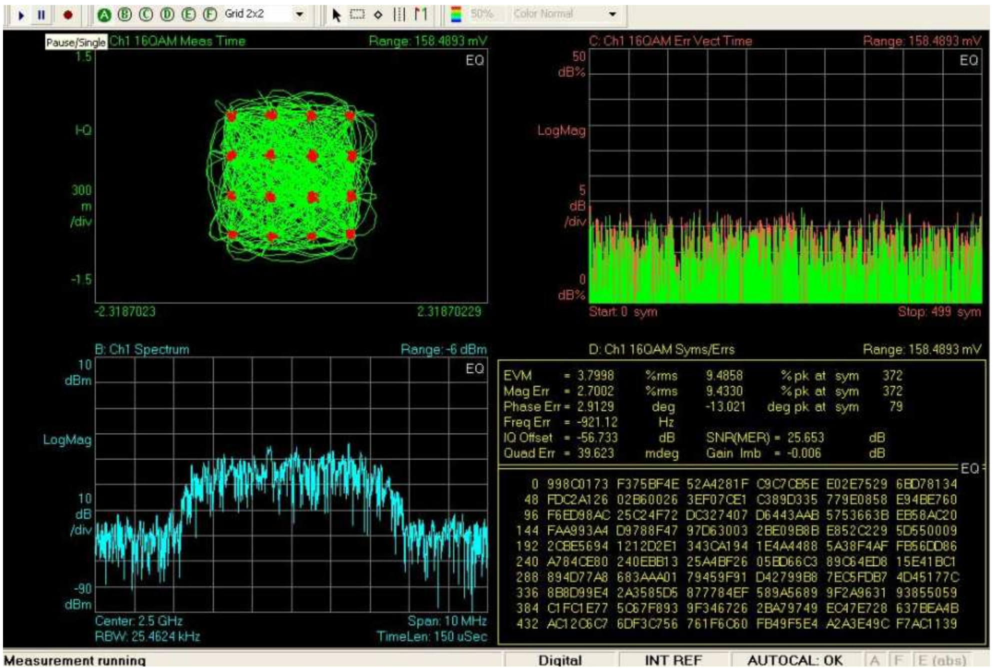


Fig.3.17. VSA results for an attenuation loss of 6 dB

The results are very similar to which were obtained in the back-to-back configuration, with the slightly variations in the EVM.

<u>- Attenuation loss = 32 dB:</u>

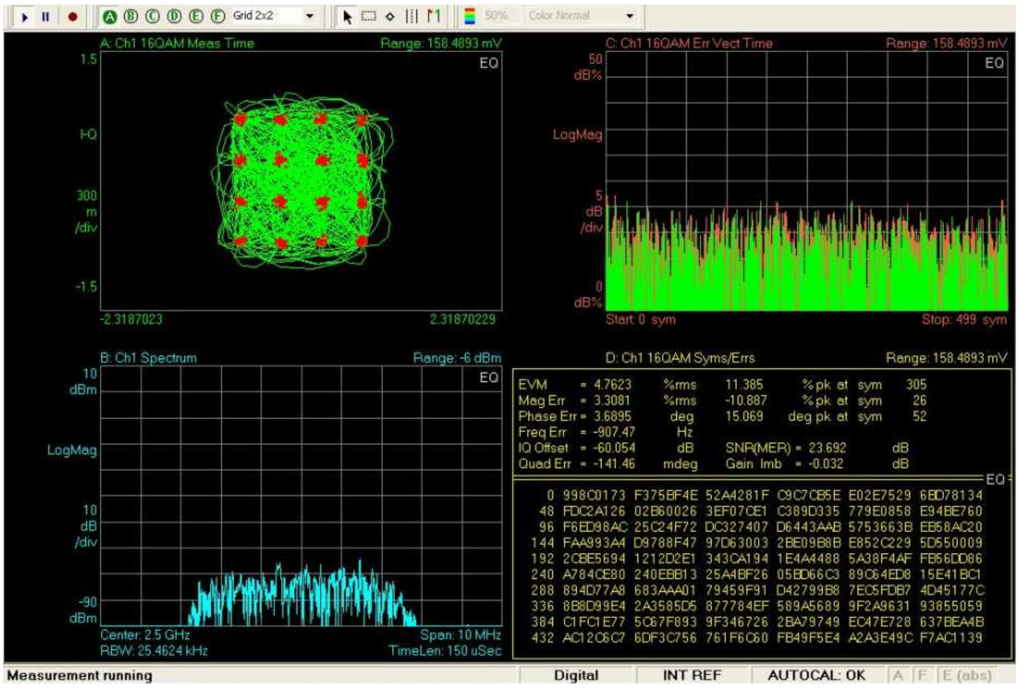


Fig.3.18. VSA results for an attenuation loss of 32 dB

In this case, it can be perceived that the constellation is still shown very clear, and the EVM trace has not experimented significant increase from the previous figure, since only a slightly variation of 1% has appeared. However, there is a meaningful difference in the spectrum trace. It has considerably decreased, which indicates that from this transmission distance, the quality of the system will start to deteriorate.

<u>- Attenuation loss = 38 dB:</u>

As predicted, the constellation has become worse and the EVM versus time trace has significantly increased, being unable to keep the quality of the link performance.

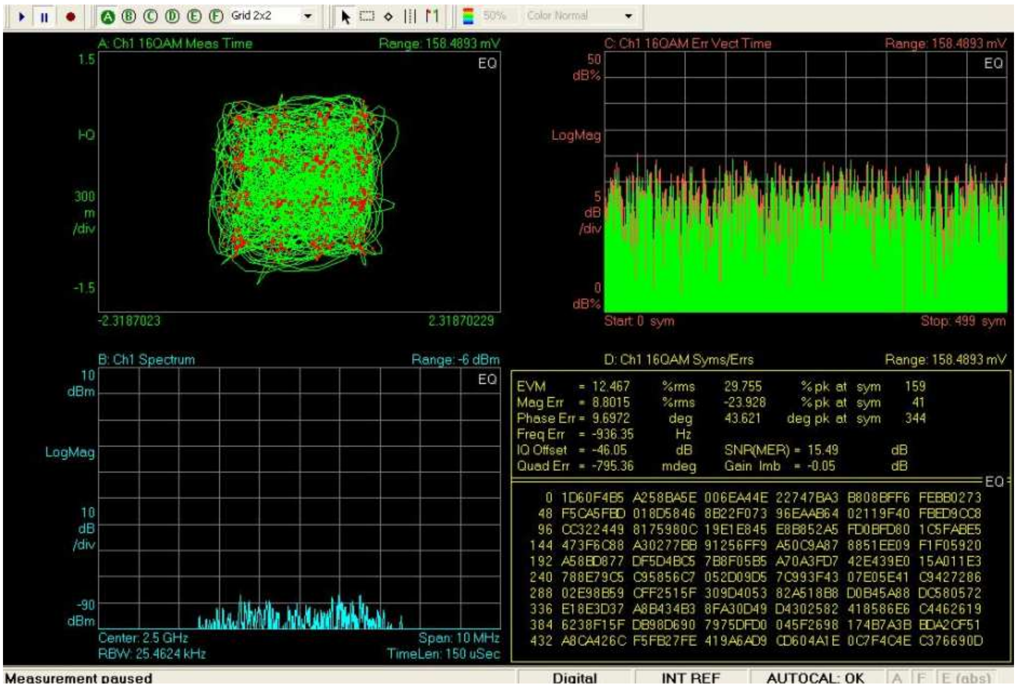


Fig.3.19. VSA results for an attenuation loss of 38 dB

Below the curves of EVM and BER against the attenuation loss are presented.

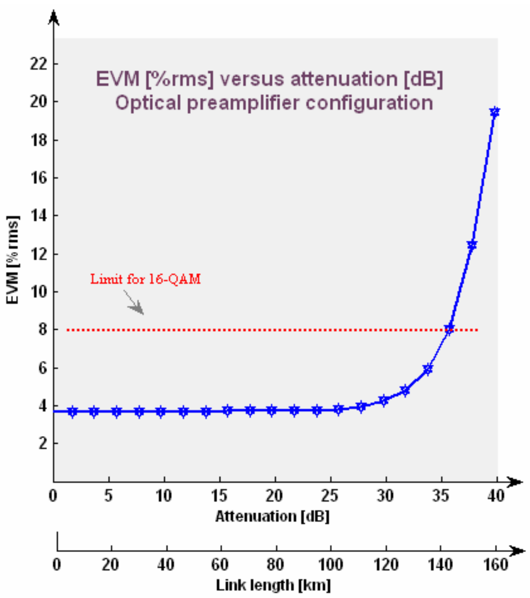


Fig.3.20. EVM vs. attenuation loss (optical preamplifier)

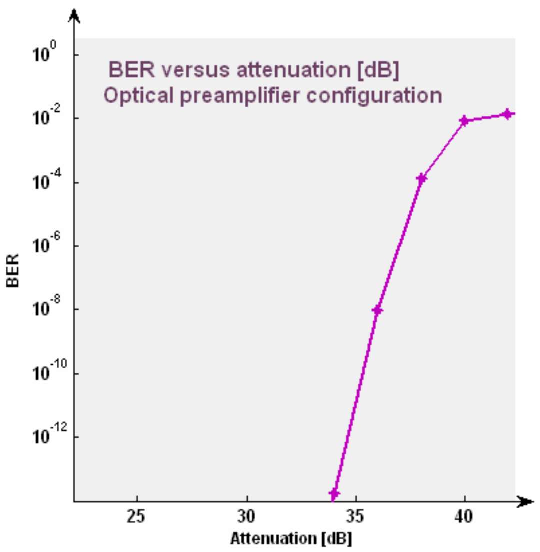


Fig.3.21. BER vs. attenuation loss (optical preamplifier)

As seen, the EVM has a constant value of approximately 3.7 % - 4.0 % until a link length in the order of 120 km. From this value, the EVM begins to rise until it reaches the EVM limit for the fixed 16-QAM transmission, which corresponds to a transmission distance of about 140 km, and from this, there is an abrupt augment.

By examining the BER curve, it can be seen that it is very similar to the BER in the back-to-back case, with the difference that, for a given BER of 10^{-12}, the attenuation loss of the fibre is around 35 dB, a difference of 10 dB compared to the first configuration.

In-line amplifier configuration

As assumed before, the first attenuator is set to a value of 24 dB, corresponding to the SOA gain, so as to study the effect of the second attenuator.

In accordance with the EVM limit of 8% set for 16-QAM transmission, a distance of approximately 40 km can be reached one in-line SOA block (corresponding to 10 dB of attenuation loss). The achievable optical power in this case results to be around -24.8 dBm, corresponding to an EVM of 7.8 % and a SNR around 22.15 dB.

Error free transmission, which corresponds to a BER less than 10^{-15}, is achieved until a transmission length of 32 km, which corresponds to 8 dB of attenuation loss and an EVM of around 5.52 %rms.

Since the link length has decreased to the half EVM value given by the back-to-back case, it means that the SOA may not be compensating for fibre losses. By adding additional SOA stages, the achievable link length would be extended, but the EVM would also be degraded.

If the fibre loss of the first SMF path was smaller than the SOA gain, that is to say, smaller fibre length, the experimental results would have been different.

New measurements could be performed by considering both attenuators as variable. For matter of time, these could not be carried out.

Below are presented the results for this configuration.

- Attenuation loss = 0 dB:

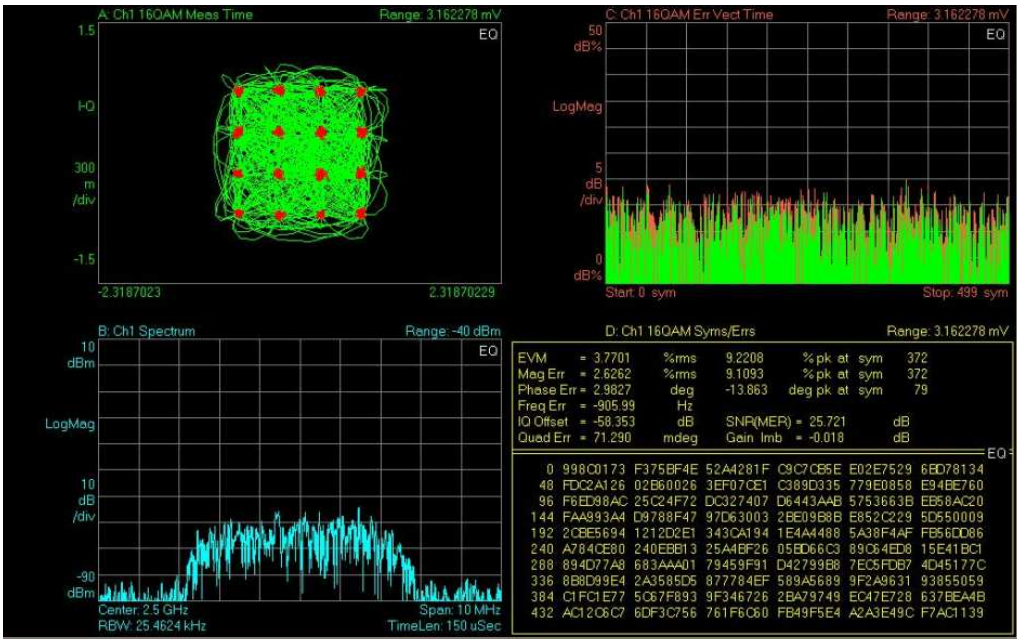


Fig.3.22. VSA results for an attenuation loss of 0 dB

The minimum EVM value obtained for this configuration is 3.77 %, which would correspond to a fibre without losses before the receiver. In practice, this is unrealizable, so, with the intention of studying the effect of the second fibre placed after the SOA, the attenuation loss is increased

- Attenuation loss = 5 dB:

When increasing the second attenuator value to 5 dB, slightly EVM degradations of 1% are observed. The constellation remains clear enough, but the spectrum starts to disappear, for the chosen range of -40 dBm.

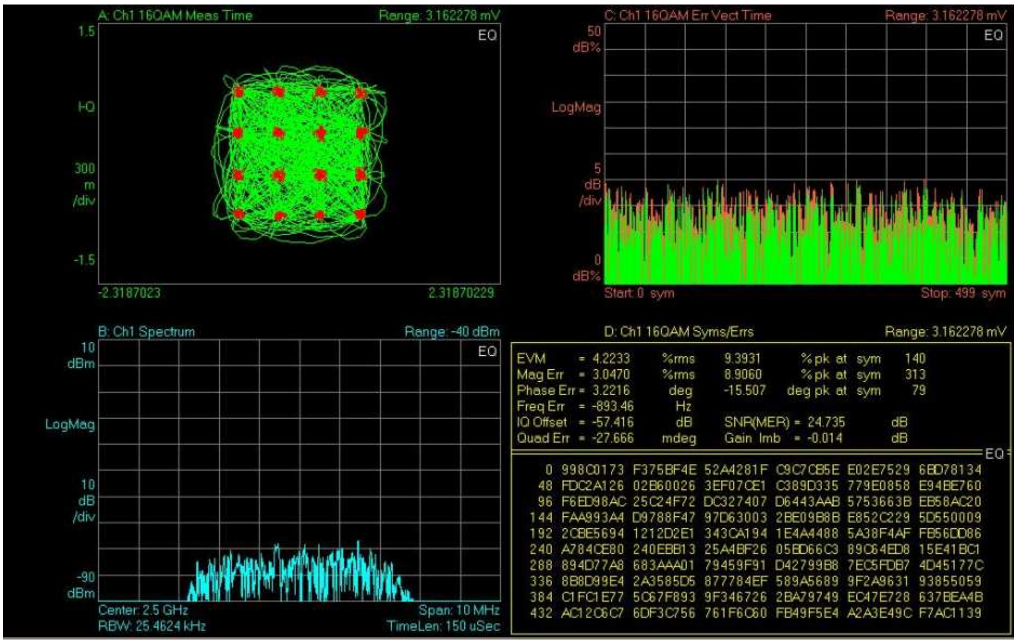


Fig.3.23. VSA results for an attenuation loss of 5 dB

- <u>Attenuation loss = 10 dB:</u>

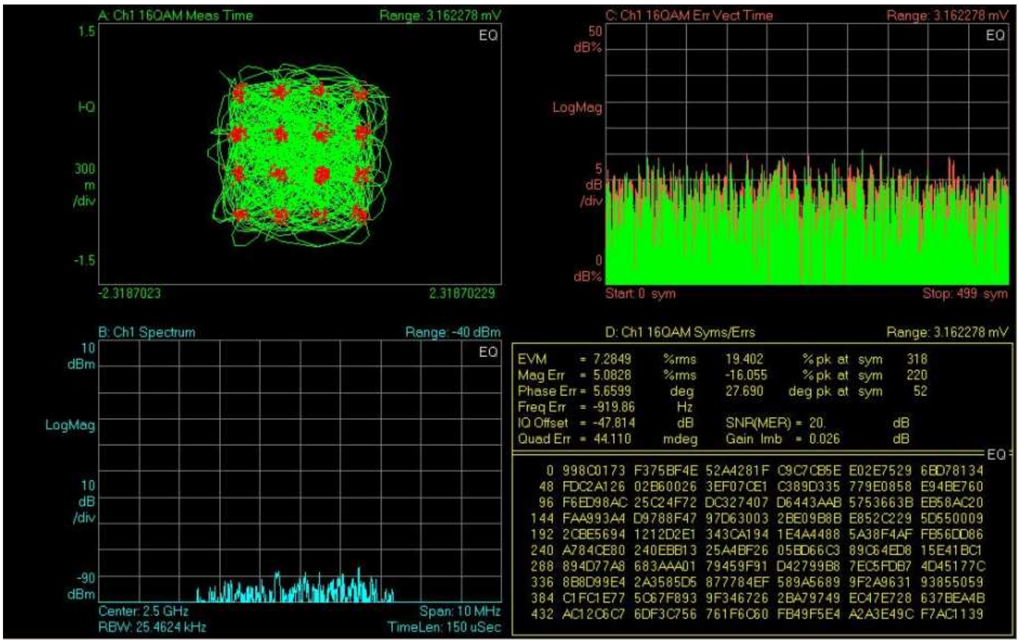


Fig.3.24. VSA results for an attenuation loss of 10 dB

When the fibre loss modelled by the second attenuator reaches 10 dB, the constellation gets worse, showing errors between adjacent symbols. The spectrum is unable to distinguish and the EVM reaches the fixed limit for an acceptable transmission.

These effects are illustrated below, with plot of the EVM and BER against the attenuation loss, and, though the shape is the same as the two previous configurations, the achievable link length with one SOA block is inferior, and the BER is worse for smaller attenuation values.

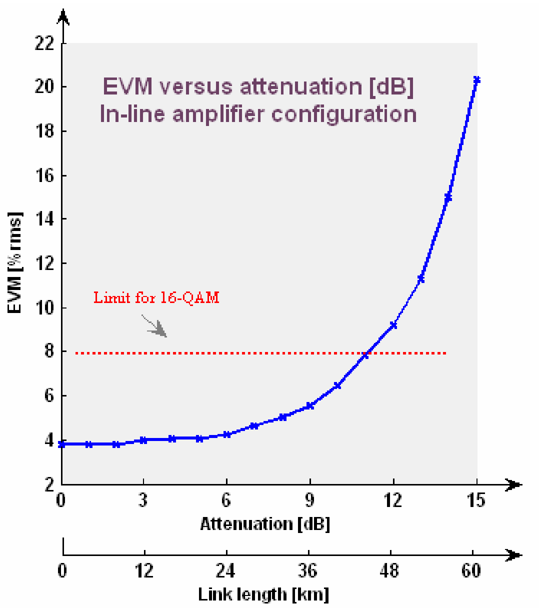


Fig.3.25. EVM vs. attenuation loss (in-line amplifier)

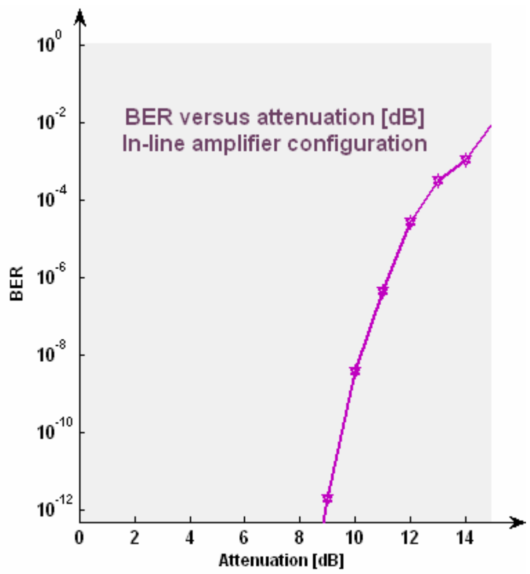
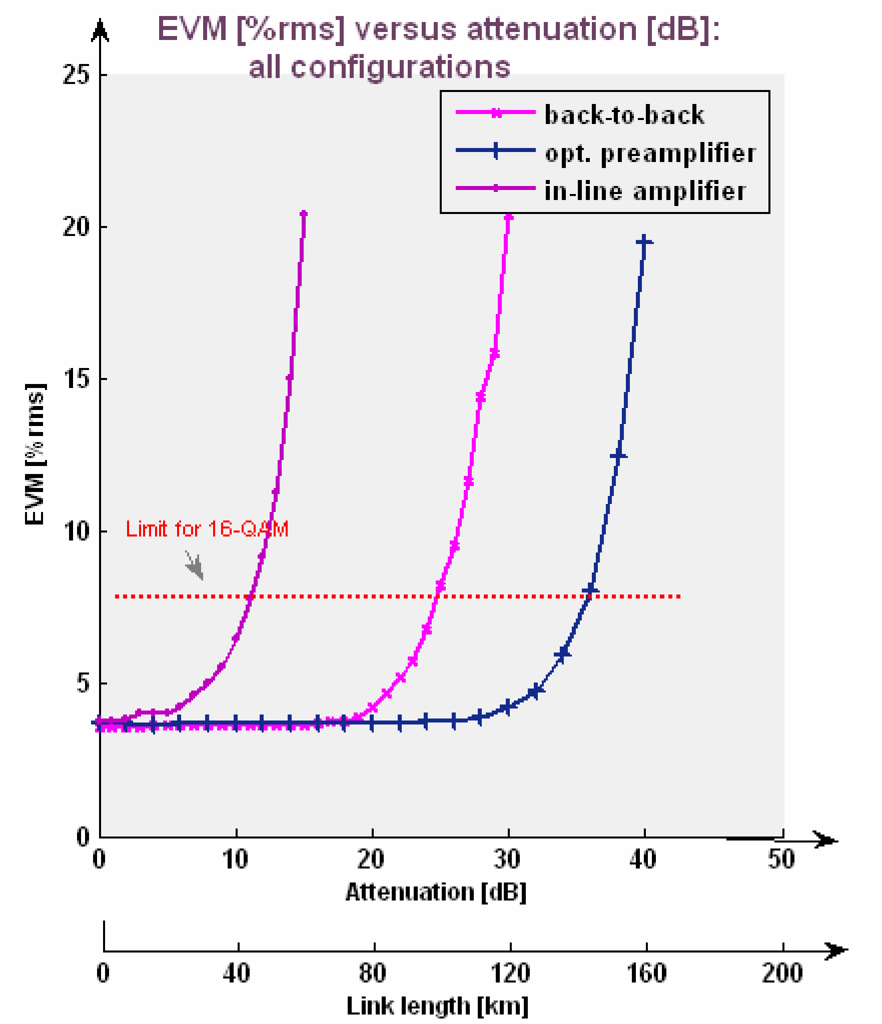


Fig.3.26. BER vs. attenuation loss (in-line amplifier)

In *fig.3.27.*, the long-haul fibre link performance comparison of the three studied configurations is shown. It can be perceived the difference between the transmission distances in the three system setups. As mentioned, for the back-to-back configuration, the achievable link length is set around 100 km, being able to reach up to 144 km of transmission distance with one SOA block in an optical preamplifier configuration, and a smaller link length with one SOA as in-line amplifier.

It can be seen that with a SOA block placed before the receiver, the achievable link length respecting to the back-to-back case is extended by about 40 km with a slightly degradation in the system performance. However, when using one single SOA block as an in-line amplifier, the achievable link length is significantly reduced, which can be a reason to think that the SOA is not compensating for the fibre loss.



Chapter 4. Conclusions

In this paper, an optical communications system has been arranged, and has been experimentally investigated how the performance is limited by the effects of noise and attenuation.

In this experiment, a 16 Mb/s 16-QAM signal was transmitted over 144 km of SMF with a BER less than 10^{-12}, at a carrier frequency of 2.5 GHz and one SOA block as an optical preamplifier. It could not be demonstrated the successful transmission utilizing an in-line amplifier, being unable to compensate for the fibre losses and then achieving a lower link length.

For signal transmission modelling, a VSG was used in collaboration with Matlab tools and obtain the source signal subsequently injected into the laser. So as to evaluate the quality of the three experiment setups (*back-to-back configuration, optical preamplifier* and *in-line amplifier*), two figures of merit were considered: EVM and BER.

EVM measurements were used to obtain information and observe the effects under varying the link length. The results and trends achieved were in agreement with what was expected from theory, to be precise, attenuation loss growth with link length, and also caused increases in BER (related to the EVM by the equations 2.5 and 2.6). Besides, it was demonstrated in all the cases that, as the transmission length increased at 16 Mb/s, the signal strength and SNR decreased due to signal attenuation.

Finally, it is worth mentioning that there was an attempt of carrying out the experiment with a QPSK signal, so as to compare results for both modulations, but finally, the equipment limitations didn’t allow to perform the measurements in a good-quality.

4.1. Future work

This section covers possible system modifications so as to improve the system parameters, i.e. data rate, link length or error measurements.

Referring to the transmission signal, other modulation schemes with higher levels than 16-QAM could be used and achieve greater bandwidth efficiency, such as 32-QAM or 64-QAM. Further measurements could be performed and set comparisons between them.

The system arrangement could be carried out at higher data rates and symbol rates. So that it could be achieved, additional options should be installed on the VSA software, in order to allow a frequency span of 25 MHz, instead of the actual 10 MHz.

Finally, with the purpose of increasing the span limit of the link, more SOA stages could be used in a cascaded configuration as in-line amplifiers, and compensate for the fibre losses.

4.2. Author's conclusions

The impression I get from this project is enormously positive. I have been working on a research project during 6 months, in which I have reviewed telecommunication concepts and applied them in practice. Moreover, I have gained experience in programming in Matlab, have learned how to use new complex equipment and acquired enough knowledge to solve problems when they appeared, and I have won patience and confidence to develop a complicated task and find the solution when I felt stuck.

One of the most important things that I've learned is working in a project on my own, which required looking for technical and stuff support, distributing time and making decisions.

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Appendix A: Matlab Code

16QAM_final.m

Schematically, this code in Matlab performs the following tasks:

```
1.) Create the IQ waveform of a 16QAM
2.) Save the waveform into the ESG/PSG Internal Arb format
     This format is for the N5182A, E4438C, E8267C, E8267D
     This format will not work with the ESG E443xB
3.) Load the internal Arb format file into a MatLab array
```

```
% 1.) Create IQ Signals for 16 QAM
*****************************************

% PARAMETERS DEFINITION
M = 16;                         % Size of signal constellation
k = log2(M);                    % Number of bits per symbol
points = 12500;                 % Number of points per bit
nsamp = 4;                      % Upsampling rate

%% SIGNAL SOURCE
% Create a binary data stream as a column vector, and a known
% vector containing all the symbols of a 16QAM constellation, to
% ensure that all the symbols will be demodulated
data = randint(points,1);       % Random binary data stream
preamble = [0 0 0 0 0 0 0 1 0 0 1 0 0 0 1 1 0 1 0 0 0 1 0 1 0 1
1 0 0 1 1 1 1 0 0 0 1 0 0 1 1 0 1 0 1 0 1 1 1 1 0 0 1 1 0 1 1 1
1 0 1 1 1 1].';                 % Preamble sequence of 64 bits

burst = [preamble;data];

%% BIT-TO-SYMBOL MAPPING
% Convert the bits in burst into k-bit symbols (Gray coding)
% A. Define a vector for mapping bits to symbols using Gray
% coding. The vector is specific to the arrangement of points in
% a 16-QAM constellation.
mapping = [0 1 3 2 4 5 7 6 12 13 15 14 8 9 11 10].';

% B. Do ordinary binary-to-decimal mapping.
xsym = bi2de(reshape(burst,k,length(burst)/k).','left-msb');

% C. Map from binary coding to Gray coding.
xsym = mapping(xsym+1);
```

```
%% MODULATION
% Modulate using 16-QAM and get the constellation values
% Applying the qammod function to a vector of integers between 0
% and 15 results in an output vector containing all points in
% the 16-QAM signal constellation.
y = qammod(xsym,M);

% Plot the transmitted constellation before adding noise and
% filtering the signal
scatterplot(y); title('QAM Scatter Plot before filtering')

% Give the I and Q components before filtering
Iwave = real(y);    % Gives the I component of the modulated data
Qwave = imag(y);    % Gives the Q component of the modulated data

% plot the in-phase and quadrature waveforms
% figure;plot(Iwave,':sr')
% xlabel('time')
% ylabel('amplitude')
% title('I&Q plot')
% hold on
% plot(Qwave,'-oc')
% hold off


%% FILTERING. Filter the I and Q signals, using
% raised cosine filters (RRC filters)

%% Filter Definition. Define filter-related parameters.
rolloff = 0.5;                % Rolloff factor of filter
filtorder = 80;               % Filter order
delay = filtorder/(nsamp*2);  % Group delay (# of input samples)

% Create a square root raised cosine filter.
rrcfilter = rcosine(1,nsamp,'fir/sqrt',rolloff,delay);

% Plot impulse response.
% figure; impz(rrcfilter,1);


%% TRANSMITTED SIGNALS
% Upsample and apply square root raised cosine filter to I and Q
% waveforms
y_tx = rcosflt(y,1,nsamp,'filter',rrcfilter);

% Create eye diagram for part of filtered signal.
% eyediagram(y_tx(1:2000),nsamp*2);
%% CHANNEL. Transmit signal through an Additive White Gaussian
```

```
% Noise channel
EbNo = 20;                                         % Eb/No in dB
snr = EbNo + 10*log10(k) - 10*log10(nsamp);        % SNR in dB
noisy_qam = awgn(y_tx,snr,'measured');

% Extract the I & Q waveforms that will be sent to the receiver
Iwavetx = real(noisy_qam);
Qwavetx = imag(noisy_qam);

% figure;plot(Iwavetx,':sr')
% xlabel('time')
% ylabel('amplitude')
% title('I&Q plot')
% hold on
% plot(Qwavetx,'-oc')
% hold off


% 2.) Save waveform in internal format
**************************************
% Convert the I and Q data into the internal arb format, which
% is a single waveform containing interleaved IQ data. (signed
% short integers, that is, 16 bits).
% The data has values scaled between +-32767 where:
%   DAC Value   Description
%    32767      Maximum positive value of the DAC
%        0      Zero out of the DAC
%   -32767      Maximum negative value of the DAC
% The internal arb expects the data bytes to be in Big Endian
format. This is opposite of how short integers are saved on a PC
(Little Endian).
% For this reason the data bytes are swapped before being saved.

% Interleave the IQ data
waveform(1:2:2*12644) = Iwavetx;
waveform(2:2:2*12644) = Qwavetx;

% Normalize the data between +/- 1, watching out for divide by
zero, and scale to use full range of the DAC
waveform = round(waveform * (32767 / max(abs(waveform))));
% Data is now effectively signed short integer values

% PRESERVE THE BIT PATTERN but convert the waveform to
% unsigned short integers so the bytes can be swapped.
% Note: Can't swap the bytes of signed short integers in MatLab.
waveform = uint16(mod(65536 + waveform,65536));
```

```
% If on a PC swap the bytes to Big Endian
if strcmp( computer, 'PCWIN' )
   waveform = bitor(bitshift(waveform,-8),bitshift(waveform,8));
end

% Save the data to a file
% Note: The waveform is saved as unsigned short integers.
% However, the actual bit pattern is that of signed short
% integers and that is how the ESG/PSG interprets them.
filename = 'C:\Temp\noisy3_QAM_EsgTestFile';

% Open a file to write data
[FID, message] = fopen(filename,'w');
if FID == -1 error('Cannot Open File'); end
fwrite(FID,waveform,'unsigned short');  % Write to the file
fclose(FID);                            % Close the file

% 3.) Load the internal Arb format file
****************************************
% This process is just the reverse of saving the waveform
     % Read in waveform as unsigned short integers.
     % Swap the bytes as necessary
     % Convert to signed integers then normalize between +-1
     % De-interleave the I/Q Data

% Open the file and load the internal format data
[FID, message] = fopen(filename,'r');  % Open file to read data
if FID == -1 error('Cannot Open File'); end
[internalWave,n] = fread(FID, 'uint16'); % Read the IQ file
fclose(FID);                             % Close the file

% Transpose: Convert from column array to row array
internalWave = internalWave';
% If on a PC swap the bytes back to Little Endian
if strcmp( computer, 'PCWIN' )  % Put the bytes into the correct
order
   internalWave= bitor(bitshift(internalWave,-
8),bitshift(bitand(internalWave,255),8));
end

% convert unsigned to signed representation
internalWave = double(internalWave);
tmp = (internalWave > 32767.0) * 65536;
iqWave = (internalWave - tmp) ./ 32767;  % and normalize the
data

% De-Interleave the IQ data
IwaveIn = iqWave(1:2:n);
QwaveIn = iqWave(2:2:n);
```

Appendix B: Measurement tables

1. Back-to-back configuration

Attenuation [dB]	Optical power (dBm)	EVM [%rms] *	SNR [dB] **	BER
0	1,3	3,60	28,87	7,9455e-36
1	0,4	3,60	28,86	9,4805e-36
2	-0,5	3,60	28,86	1,1310e-35
3	-1,5	3,60	28,85	1,1310e-35
4	-2,5	3,61	28,85	1,1924e-35
5	-3,5	3,61	28,85	1,2352e-35
6	-4,5	3,61	28,84	1,2795e-35
7	-5,5	3,61	28,84	1,4221e-35
8	-6,5	3,61	28,83	1,5529e-35
9	-7,5	3,62	28,82	1,9178e-35
10	-8,5	3,62	28,82	2,0216e-35
11	-9,6	3,62	28,81	2,1687e-35
12	-10,6	3,63	28,80	2,7725e-35
13	-11,6	3,64	28,77	4,6871e-35
14	-12,6	3,64	28,77	4,6871e-35
15	-13,6	3,65	28,75	6,6449e-35
16	-14,6	3,73	28,56	1,6715e-33
17	-15,6	3,76	28,49	5,3081e-33
18	-16,6	3,80	28,40	2,2971e-32
19	-17,6	3,89	28,20	5,2583e-31
20	-18,6	4,25	27,43	2,6505e-26
21	-19,6	4,68	26,59	5,0579e-22
22	-20,6	5,22	25,64	4,2239e-18
23	-21,6	5,74	24,82	2,5230e-15
24	-22,6	6,82	23,32	2,1081e-11
25	-23,6	8,24	21,68	2,1571e-8
26	-24,6	9,56	20,39	1,0889e-6
27	-25,6	11,67	28,65	4,8391e-5

28	-26,6	14,43	16,81	7,3277e-4
29	-27,6	15,84	16,00	1,7933e-3
30	-28,6	20,36	13,82	1,0565e-2

* As a matter of fact, EVM [%rms] values are four digit numbers rounded up to two digits.
** SNR [dB] values are calculated using the expression (II) given in **section 2.2.2.**, for the four digit EVM values, so as to get more accurate results for BER.

2. Preamplifier configuration

Attenuation [dB]	Optical power (dBm)	EVM [%rms]	SNR [dB]	BER
0	4,6	3,68	28,68	2,2019e-34
2	4,3	3,69	28,65	3,6961e-34
4	3,8	3,70	28,63	5,2153e-34
6	3,2	3,70	28,65	5,2153e-34
8	2,3	3,69	28,65	3,6961e-34
10	1,7	3,69	28,65	3,6961e-34
12	0,7	3,69	28,65	3,6961e-34
14	-0,7	3,69	28,65	3,6961e-34
16	-2,4	3,71	28,61	7,3530e-34
18	-4,2	3,73	28,56	1,7295e-33
20	-6,1	3,74	28,54	2,4315e-33
22	-8,1	3,74	28,54	2,4315e-33
24	-10,0	3,76	28,49	5,6798e-33
26	-12,0	3,80	28,40	2,1845e-32
28	-14,0	3,90	28,17	8,3112e-31
30	-15,9	4,26	27,41	3,4714e-26
32	-17,8	4,78	26,41	3,3511e-21
34	-19,6	5,92	24,55	1,7929e-14
36	-21,3	8,01	21,92	9.4430e-09
38	-23,0	12,46	18,08	1,2639e-04
40	-24,5	19,45	14,22	8,0803e-03
42	-25,08	21,26	13,45	1,3302e-02

3. In-line amplifier

Attenuation [dB]	Optical power (dBm)	EVM [%rms]	SNR [dB]	BER
0	-14,7	3,77	28,47	7.9635e-33
1	-15,7	3,79	28,42	1.8472e-32
2	-16,7	3,81	28,38	3.6083e-32
3	-17,7	4,01	27,94	2.8724e-29
4	-18,7	4,02	27,91	3.9450e-29
5	-19,7	4,22	27,49	1.2112e-26
6	-20,7	4,62	26,70	1.4694e-22
7	-21,8	5,01	26,00	1.6913e-19
8	-22,8	5,52	25,16	2.0034e-16
9	-23,8	6,47	23,78	1.9315e-12
10	-24,8	7,80	22,15	3.8206e-09
11	-25,8	9,18	20,74	4.2944e-07
12	-26,8	11,26	18,97	2.6510e-05
13	-27,8	13,41	17,45	3.2183e-04
14	-28,8	15,01	16,47	1.1173e-03
15	-29,8	20,35	13,83	1.0641e-02

Appendix C: Data Sheet

VSG specifications:

Agilent N5182A MXG -Vector Signal Generator. Data Sheet, Literature number 5989-5261EN

VSA specifications:

Agilent Technologies Company, "*89601X VXA Signal Analyzer-Measurement Guide-Agilent EXA and MXA Signal Analyzers", Manufacturing Part Number: 89601-90002*, USA (2008)

Filter

Optical Tunable Filter OTF-910, Santec

3 dB Bandwidth: 0.49 nm

Attenuator 1

Optical attenuator HP 8156A

1310/1550 nm

Insertion loss: 3 dB

Attenuator 2

Optical attenuator HP 8156A

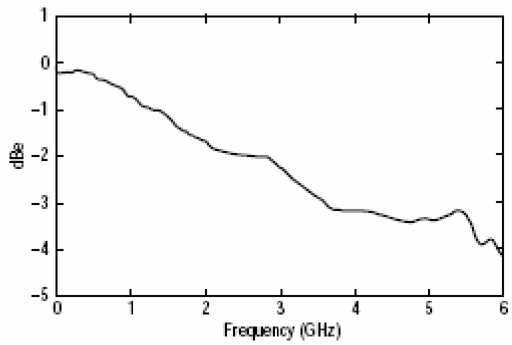
1310/1550 nm

Insertion loss: 2.4 dB

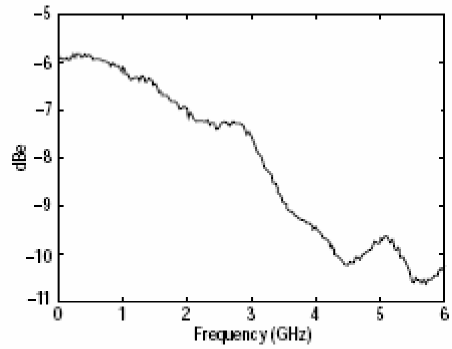
Lightwave Source Specifications

HP 83403-C. Lightwave source 1550nm +/- 30 nm

Specifications and *Characteristics (in italics)*	Agilent 83402C	Agilent 83403C
Center wavelength[8,9]	1310 ±30 nm	1550 ±30 nm
Center wavelength stability[9]	*0.3% per year*	*0.3% per year*
Spectral Width[8,9]	*<50 MHz*	*<50 MHz*
Average optical output power[8,9]	2000–3000 μW	2000–3000 μW
Optical port return loss	*≥35.0 dBo*	*≥35.0 dBo*
Modulation range	300 kHz to 6 GHz	300 kHz to 6 GHz
RF input power (max)	*+11 dBm*	*+11 dBm*
DC into RF port (max)	20 V	20 V
Electrical port return loss[10]	≥11 dB	≥11 dB
Modulation frequency response (300 kHz to 6 GHz)[8]		
Corrected (disk) (specification)	±0.5 dBe	±0.5 dBe
Corrected (disk)	*±0.31 dBe*	*±0.31 dBe*
Corrected (polynomial)	*±1.5 dBe*	*±1.5 dBe*
Uncorrected	*±0.2/–4.8 dBe*	*+0.2/–4.8 dBe*
Responsivity at 140 MHz modulation frequency	*0.053 W/A (–25.5 dBe)*	*0.053 W/A (–25.5 dBe)*
Modulation (harmonic) distortion[11]		
300 kHz to 1 GHz	*25.0 dBc*	*25.0 dBc*
1 GHz to 3 GHz	*(footnote 12)*	*(footnote 12)*
1 GHz to 6 GHz	*8.0 dBc*	*8.0 dBc*
Third order intercept (min)[11]	*23 dBm*	*23 dBm*
1 dB modulation compression level at 50 MHz	—	—
Equivalent Input Noise		
0.01 to 5 GHz	*–124 dBm/Hz*	*–124 dBm/Hz*
5 to 6 GHz	*–119 dBm/Hz*	*–119 dBm/Hz*
Reflection Sensitivity (300 kHz to 6 GHz)[13]	*±0.04 dBe*	*±0.04 dBe*
Laser Type	DFB	DFB
Laser Class	FDA Class I and IEC Class IIIB	FDA Class I and IEC Class IIIB
Optical Fiber	9/125 μm	9/125 μm



Agilent 83402C modulation frequency response (characteristic)



Agilent 83403C modulation frequency response (characteristic)

8 Factory test system
9 No intensity modulation applied.
10 Measured on 8703 from 130 MHz to 6 GHz.
11 Measured with +10 dBm RF input power 0.01 to 6 GHz.
12 Changes linearly from 25 dBc at 1 GHz to 8 dBc at 3 GHz.
13 To a Fresnel reflection using a 9:1 optical coupler, averaging factor = 16

SOA specifications

Kamelian Ltd.

Maximum Ratings:

- Operating case Temperature: -5 to 70 ºC
- Reverse voltage: < 3 V
- Forward Current: < 270 mA
- TEC cooler Current: < 2.0 A

Test Summary

All tests performed with a chip temperature of 20 ºC and a case temperature of 25 ºC

Parameter	Condition	Value	Units
Forward Voltage	I_f = 450 mA	2.13	V
Fibre 1	I_f = 435 mA	15.27	mW
Fibre 2	I_f = 430 mA	14.38	mW
Fibre to Fibre Gain	1528 nm, Pin = -25 dBm, I_f = 270 mA	27.46	dB
	1550 nm, Pin = -25 dBm, I_f = 270 mA	23.88	dB
	1563 nm, Pin = -25 dBm, I_f = 270 mA	20.98	dB
Noise Figure	1528 nm, Pin = -25 dBm	6.37	dB
	1550 nm, Pin = -25 dBm	6.19	dB
	1563 nm, Pin = -25 dBm	6.20	dB
Saturation Output Power	1528 nm, I_f = 270 mA	12.98	dBm
	1550 nm, I_f = 270 mA	13.65	dBm
	1563 nm, I_f = 270 mA	13.71	dBm
Polarisation Dependent Gain	1528 nm, Pin = -25 dBm, I_f = 270 mA	0.57	dB
	1550 nm, Pin = -25 dBm, I_f = 270 mA	0.08	dB
	1563 nm, Pin = -25 dBm, I_f = 270 mA	0.61	dB
Gain Ripple	1528 nm	0.57	dB
	1550 nm	0.06	dB
	1563 nm	0.61	dB
3 dB Bandwidth	I_f = 270 mA	42	nm
Centre Wavelength	I_f = 270 mA	1480	nm

Amplifier Lightwave converter

Specifications describe the instrument's warranted performance over the 0 °C to 55 °C temperature range, except where noted. **Characteristics** provide information about non-warranted instrument performance in the form of nominal values. All amplitude specifications are in optical power units unless noted by an asterisk(*).

Specifications/Characteristics

Wavelength (characteristic)	*1200 nm to 1600 nm*
Bandwidth (characteristic)	*dc to 15 GHz (optical)* *dc to 11 GHz (electrical)*
Full Width Half Maximum (calculated from FWHM = 0.44/BW opt)	29.4 ps
Conversion Gain (dc responsivity)[1] (provided value accurate to ±20%)	> 200 V/W 300 V/W, nominal
Noise Equivalent Power[2] (characteristic)	*30 pW/√Hz*
Input Return Loss (characteristic with HMS-10/Diamond connector)	*> 23 dB*
Aberrations (characteristic)	*< 20% peak-to-peak*
Corrected Freq Response[3] dc – 22 GHz	20 to 30°C ±2.2 dB* 0 to 55°C ±4.7 dB*
Harmonic Distortion Output < –10 dBm	> 41 dB* below fundamental
Maximum Safe Optical Input Power (average)	10 mW (+10 dBm)
Maximum Operating Optical Input Power (peak)	1.5 mW (+1.76 dBm)
Output Voltage Range (into 50 ohms)	> 700 mV
Output Offset Voltage (into 50 ohms)	< 1 mV
Output Electrical Return Loss 0.1 to 12 GHz (characteristic) 12 GHz to 22 GHz	 *> 11 dB** > 9 dB*

Inputs/Outputs

Optical Input Connector (front panel)	Single Mode Fiber Connectors: Diamond HMS 10, FC/PC, ST, DIN
Output Connector (front panel)	APC 3.5, male, 50 ohms (nominal)

General

Environmental Temperature Range	 Operational 0 to +55 °C Storage –40 to +75 °C
EMI	Conducted and radiated emission are in compliance with the requirements of FTZ 1046; CISPR Publication 11 (1975); and MIL-STD-461C, Part 7, Methods CE03 and RE02.
Power Requirements	100, 120, 220, or 240 volts (±10%), 47–63 Hz Power consumption <75VA
Weight	3.76 kg (8.4 lb)
Dimensions	102 mm (4.02") height, 213 mm (8.39") width, 368 mm (14.49") length

* Refers to electrical power units
1 ± Connector variation
2 = 3.7 μW in a 15 GHz bandwidth
3 Corrections are either downloaded into the Agilent 8593E, 8594E or 8595E spectrum analyzer or obtained from the calibration chart.

```
ERROR: syntaxerror
OFFENDING COMMAND: --nostringval--

STACK:

/Title
(Optical communications)
/Subject
(D:20080610160058)
/ModDate
()
/Keywords
(PDFCreator Version 0.8.0)
/Creator
(D:20080610160058)
/CreationDate
(Rosa M‹ RoldÆn)
/Author
-mark-
```