DEPARTMENT OF PHYSICS

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DEVELOPMENT OF AN OPTICAL AMPLIFIER FOR COMMUNICATION BETWEEN AN AIRCRAFT AND A SATELLITE

MASTER IN PHYSICS ENGINEERING

NOVA School of Science and Technology
September, 2024

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ACKNOWLEDGMENTS

É difícil assumir que este documento é o ponto final de um longo caminho de 5 anos. 5 anos que foram certamente os melhores anos da minha ainda curta vida. No entanto, não me seria possível estar aqui, a poucas horas da oficialização deste ponto final, sem agradecer àqueles que me ajudaram a chegar a este ponto em que estou.

Em primeiro lugar, quero agradecer a quem foi a minha segunda casa (por uma curta margem às vezes) durante estes anos, a quem foi alegrias e tristezas e a quem foi e será memórias e saudades. Obrigado, FCT!

Quero agradecer, também, a quem me deu a conhecer o mundo fantástico da Engenharia, a quem me fez gostar ainda mais de Física e a quem me deu a oportunidade de crescer. Obrigado, Lusospace, e mais concretamente ao Nuno Franco! Alguém que teve um papel importantíssimo na realização desta tese, que mais me entusiasmou com tudo isto e que, com a sua boa disposição, me fez sempre ver o lado positivo durante todo este processo.

Quero agradecer a quem me fez gostar de Vibrações e Ondas, Ótica e Aplicações Avançadas da Instrumentação, a quem me ensinou tanto durante estes 5 anos e a quem me fez ver ainda mais o quão interessante é a Física. Obrigado, Professor Pedro Vieira!

E como, felizmente, estes anos não podem ficar resumidos apenas a este documento…

Quero agradecer aos primeiros a darem-me os parabéns nesse já distante dia 7 de setembro de 2019, àqueles que mesmo não percebendo grande coisa do que fazia, foram sempre o meu primeiro socorro e àqueles que sempre compreenderam e me deixaram voar nesta fase tão importante para mim. Obrigado, pais e irmãos!

Quero agradecer a quem eu tive a felicidade de conhecer e desde então esteve sempre do meu lado, àquela com quem partilho tantas emoções e memórias e a quem me faz ser uma pessoa melhor, todos os dias. Obrigado, Pipa!

Quero agradecer a quem esteve lá desde o primeiro momento, a quem me fez rir tanto e àqueles com quem tive a possibilidade de partilhar todos os sucessos e desgostos. Obrigado, Ana, Bá, Cat, Fon, Maggie, Minnie e Veggie! Obrigado, Bang! This is the end of the beginning.

Quero agradecer a quem foi um exemplo para mim, a quem me deu tantos conselhos e a quem eu escolheria novamente. Obrigado, Bia e Joana! Obrigado, madrinhas!

Quero agradecer a quem me escolheu, a quem eu dei tantos conselhos e a quem acabou, mais do que eu estaria à espera, por ser um exemplo para mim. Obrigado, Leonor, Madalena, Carlota, Antunes e Bart! Obrigado, afilhados!

Quero agradecer a quem veio antes de mim, a quem veio ao mesmo tempo e a quem veio depois de mim. Quero agradecer a todos com quem pude partilhar tantos momentos. Obrigado, amigos! Obrigado, CoPes! Obrigado, CPs! Obrigado, AEFCT! Obrigado, NEFCT! Obrigado, Física!

Obrigado a todos!

“The fool on the hill sees the Sun going down/ And the eyes in his head see the world spinning 'round.” (Lennon/McCartney).

ABSTRACT

The subject of this dissertation arises from a project of a Portuguese engineering company called Lusospace, which consists of developing an optical terminal for communication between aircraft and satellites, with the aim of making high-speed internet available on board aircraft.

This project has numerous challenges, one of which is to ensure that the modulated signal generated by the optical terminal is acquired by the satellite, which is around ten thousand kilometres away and has a relative speed of over 20000 km/h. For this to be possible, it is essential to develop an optical fibre amplifier, including the signal modulation module, with the main requirements being gain and the power ratio between the 'on' and 'off' emitted by the terminal.

The aim of this work is to find the solution that, while complying with the project specifications, provides the best result to achieve the desired result. After a theoretical study, this dissertation presents the proposed solution, its implementation and an analysis of the results.

The research work described in this dissertation was carried out in accordance with the norms established in the ethics code of Universidade Nova de Lisboa. The work described and the material presented in this dissertation, with the exceptions clearly indicated, constitute original work carried out by the author.

Keywords: Optical Fibre Amplifier, Output power, Optical Fibre, Trade-off

RESUMO

O tema desta Dissertação surge na sequência de um projeto de uma empresa portuguesa de engenharia chamada Lusospace, que consiste no desenvolvimento de um terminal ótico para a comunicação entre aeronaves e satélites, com a finalidade de disponibilizar internet de alto débito a bordo de aeronaves.

Este projeto tem inúmeros desafios, sendo um deles conseguir que o sinal modulado gerado pelo terminal ótico seja adquirido pelo satélite que está a cerca de uma dezena de milhares de quilómetros de distância e com uma velocidade relativa superior a 20000 km/h. Para que isto seja possível é imprescindível o desenvolvimento de um amplificador de fibra ótica, incluindo o módulo de modulação do sinal, tendo como principais requisitos o ganho e a relação de potência entre o "on" e "off" emitida pelo terminal.

É objetivo deste trabalho procurar a solução que, estando de acordo com as especificações do projeto, apresente o melhor resultado para atingir o pretendido. Depois de um estudo teórico, esta Dissertação apresenta a proposta de solução, a sua implementação, bem como a análise dos respetivos resultados.

O trabalho de investigação descrito nesta dissertação foi realizado de acordo com as normas estabelecidas no código de ética da Universidade Nova de Lisboa. O trabalho descrito e o material apresentado nesta dissertação, com as exceções claramente indicadas, constituem trabalho original realizado pelo autor.

Palavas chave: Amplificador de fibra ótica, *Output power*, Fibra ótica, *Trade-off*

CONTENTS

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ACRONYMS

ASE	Amplified Spontaneous Emission
COTS	Commercial of-the-shelf
CW	Continuous-Wave
EDFA	Erbium Doped Fibre Amplifier
ER	Extinction Ratio
EYDFA	Erbium-Ytterbium Doped Fibre Amplifier
FOPA	Fibre Optic Parametric Amplifiers
FPM	Four-Photon Mixing
HOA	Hybrid Optical Amplifiers
MOFA	Master Oscillator Fibre Amplifier
MOPA	Master Oscillator Power Amplifier
OFA	Optical Fibre Amplifier
OPA	Optical Parametric Amplifier
OSA	Optical Spectrum Analyser
PFA	Parametric Fiber Amplifier
SFPMA	Stimulated Four-Photon Mixing Amplifier
SMF	Single Mode Fibre
SOA	Semiconductor Optical Amplifier
WDM	Wavelength Division Multiplexer
YDFA	Ytterbium Doped Fibre Amplifier

1

INTRODUCTION

This dissertation is part of an ongoing project initiated by Lusospace to develop an optical terminal to be used in commercial aviation. Lusospace is a Portuguese company, founded in 2002 and located in Lisbon, specialized in designing, developing, integrating and testing advanced technological systems for the Space Industry.

This project aims to design an optical system for communication between aircrafts and satellites, with the purpose of providing high-speed internet on-board aircraft. The project includes the definition of all terminal requirements, either related to optics, mechanical and electronic design, as well as the final laboratory environment test to validate the terminal concept.

The theme of this dissertation resides on the development of an optical amplifier that will be included in the terminal.

Figure 1.1 illustrates a quite simplified block diagram of the overall optical terminal. Note that for confidential proposes it is not possible to further detail the terminal.

This terminal is composed by a radome to protect the terminal from the outside which is located on top of the aircraft. The radome has an optical window with an anti-reflective coating for the c-band wavelength.

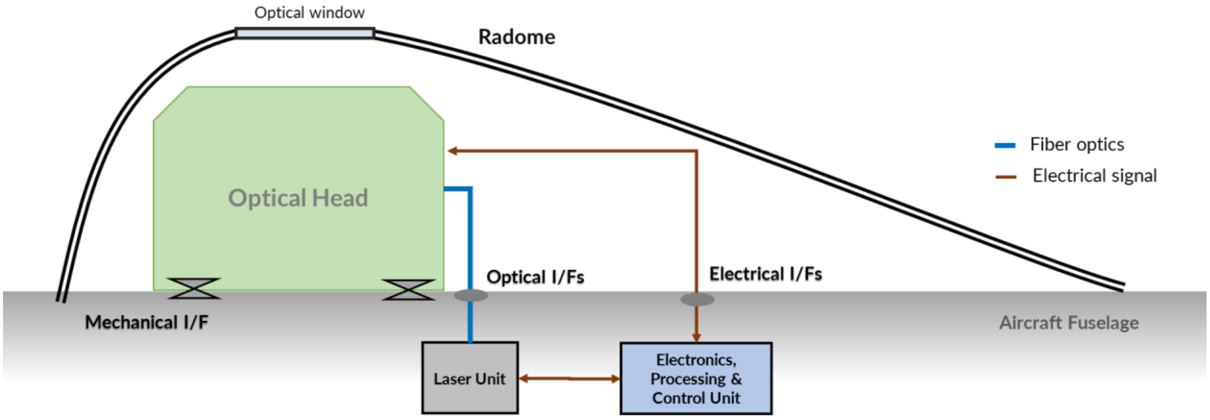


Figure 1.1 —Schematic of the optical terminal

The terminal itself can be divided into three main blocks: the Optical Head, where all optics and mechanical parts are assembled, the Laser Unit, which is part of the Tx Channel (transmission channel) including the amplifier, and the final block refers to the electronics that allows the control of the overall system.

Figure 1.2 shows an overview of an optical head, only for illustrating proposes.

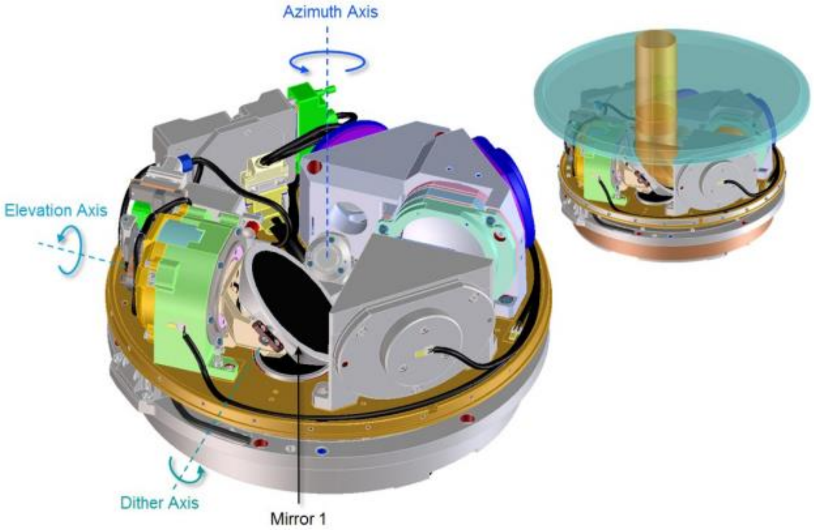


Figure 1.2 —Optical Head [16]

The optical head is an extremely complex optic-mechanical design, that, among others, has the capability to lock a laser beam (azimuth and elevation) to a satellite that travels at a relative speed of 20000 km/h including the capability of configuring the beam size at the satellite telescope for coarse point and communication.

1.1 Context and motivation

In order for a signal transmitted by the aircraft optical terminal to be received in perfect conditions by the satellite, a number of some challenging requirements must be met, such as the needed optical power, wavefront quality, the ability to direct and stabilize the beam towards the satellite with extremely high accuracy (in the order of a microrad with a bandwidth of 1 kHz) and to predict the satellite's position in relation to the aircraft.

In the context of this dissertation, the most important requirements are the signal power that should be at least 6 W with a higher than 10 dB Extinction Ratio (ER) amplitude modulation for a minimum frequency of 1 GHz using a c-band laser (1550 nm range).

Currently, there are no commercial of-the-shelf (COTS) solutions with the desired requirements. Thus, the subject of this dissertation arises in finding a solution, assemble it and test it in laboratory ambience.

1.1 Objectives

Laser amplifiers used in optical communications play a crucial role in strengthening the light signals transmitted through optical fibres, allowing long-distance communications to be more efficient. Since the project is an optical terminal for free-space communications, the goal is to use a fibre amplifier to amplify the signal, which will then be collimated to be detected by the satellite. Thus, the dissertation aims to develop an optical fibre amplifier to be integrated in the Lusospace project. For that the following tasks were defined.

Initially, the aim is to understand the optical design and understand the functionality of the optical terminal, to choose the most suitable amplifier for the system.

Subsequently, the detail study of the different Optical Fibre Amplifiers (OFA) types will be done, not only in terms of the requirements that the Optical Head (name of the project Lusospace is working on) demands, but also in terms of their implementation, analysing alternatives that can be found on the market through the literature review.

Finally, after trade-off on the existing solutions with the necessary characteristics and once the most suitable solution has been chosen, the goal is to design, assemble and test the optical amplifier, including, if necessary, experimental tests, according to the project's needs in laboratory environment.

2

THEORETICAL CONCEPTS

One of the most reliable ways to amplify an optical signal is using an optical fibre amplifier. These devices are known by their high gain, low noise and ultra stable in terms of wavelength, which is quite important when more than one channel (more than one wavelength) is used to increase the communication bandwidth.

The signal amplification is carried out along the so-called gain medium, where the signal light (low power) and the pump light (high power) are mixed.

When the pump light passes through the gain medium, it excites atoms, which will, through interaction with signal light, return to the ground state emitting light with the same frequency and phase of the incident photons (stimulated emission). The gain medium is generally made up of insulators doped with laser-active ions or made up of semiconductors elements. The doped insulators are usually crystals or glass in bulk or in fibres, and the most common laser-active ions are rare-earth elements such as Erbium, Ytterbium or Neodymium.

There are currently several optical amplifiers with slightly different operating modes, but all with the same purpose, light amplification. When choosing an optical amplifier, it is important to take into account the characteristics of each one in order to meet the desired requirements. Among the various characteristics its gain, its efficiency (directly related to saturation power), the width of the optical frequency spectrum, the noise and sensitivity to Amplified Spontaneous Emission (ASE) are some of the most important.

The ASE is a phenomenon that greatly influences the choice of amplifiers, since it is directly related to the gain of an amplifier. The ions of the gain medium that are in an excited state have a probability higher than 0 of being able to spontaneously return to the ground state by emitting a photon, as it was first predicted by Albert Einstein in 1916. This photon can then propagate along the fibre and be amplified by stimulating the emission of more photons from ions that are at higher energy levels than the ground state. This will reduce the gain of the amplifier, since this process will “steal” photons that could be emitted in a stimulated way by the signal that is actually being amplified. The ASE does not alter the small signal gain regime but only the saturation regime.

In addition to observing and studying the gain to characterize the optical amplifier and, consequently, the input and output power values, it is also important to consider the pump power. This power, with a higher energy than the signal, is pumped into the gain medium to interact with the signal and amplify it. The goal to increase the amplifier efficiency is to minimize the pump power for a defined output power.

A critical parameter that influences the amplifier performance is the fibre length. For low lengths the amplifier does not use all pump power that is being provided and it gets into saturation. This fact is due to the number of photons emitted via stimulated emission approaches the number of excited ions, leading to a state where additional input power does not result in proportional amplification. Thus, not all pump power is used to amplify the signal and it is called by Residual Pump Power.

Optical insulators that are mandatory in optical amplifiers, have a quite important role in protecting and stabilizing the system. These devices protect the system from unintended backward signals that can reach high power and damage the system components, mainly the seed laser.

Apart from the Optical Amplifier, there are components important in the final assembly and architecture of the system that it is needed to have in mind its mode of functioning, mainly the seed laser. In this case, since an amplitude modulated signal needs to be amplified, a continuous wavelength laser (constant optical power) must be used, instead of a pulse laser that can easily reach high power (> 100 W) due its operation mode, that does not allow the light modulation.

3

OPTICAL AMPLIFIERS

There is a large number of fibre optical amplifiers. In this section, it will be done a brief description of each one dividing them into categories and types within each category.

Some of the most common optical amplifiers developed are Erbium Doped Fibre Amplifiers (EDFAs), Ytterbium (YDFA), Thulium or other Rare Earth Ion Doped Fibre Amplifiers, Raman Amplifiers, Brillouin Amplifiers, Fibre Optic Parametric Amplifiers (FOPAs) or Semiconductor Optical Amplifiers (SOAs) [1]. In addition, amplifiers with more than one amplification stage are also common, such as Hybrid Optical Amplifiers (HOAs) or configurations involving a laser seed and an amplifier to increase output power, such as Master Oscillator Power Amplifier (MOPA).

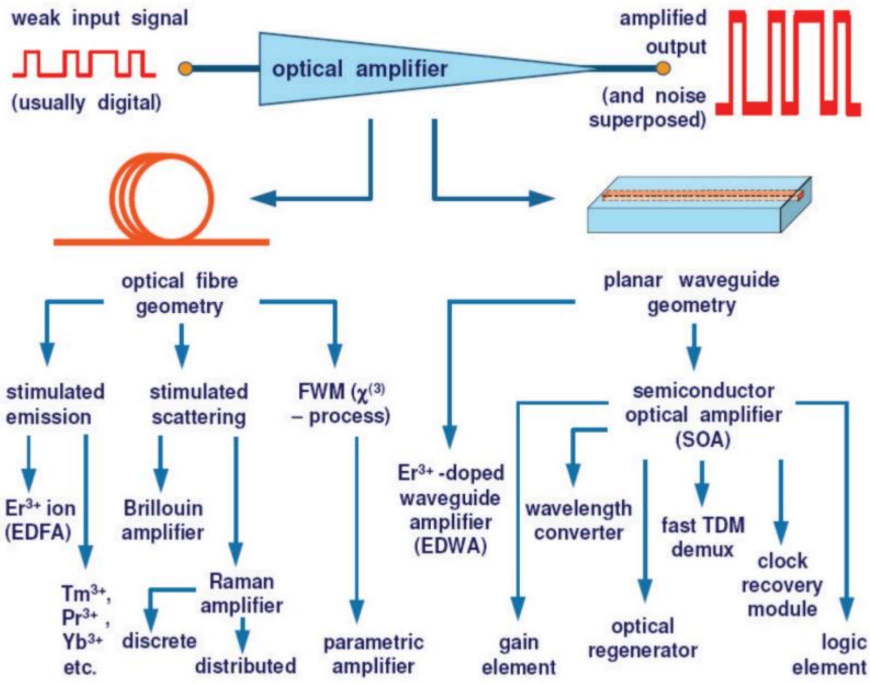


Figure 3.1 – Types of optical amplifiers for telecommunications [1]

3.1 Rare-Earth Doped Fibre Amplifiers

These amplifiers are essentially an optical fibre with a rare-earth doped core, being their absorption spectrum and energy levels that define the wavelength range of the amplified light.

The amplification process begins when an ion in the ground state is excited by a photon from the pump (higher energy), which stay at a higher energy level for a short time, decaying to a lower metastable energy level. Finally, after this ion interacts with the signal photon, it decays to the ground state emitting a photon (stimulated emission) with the same wavelength and phase as the signal [2]. This is the basis of the stimulated emission process of all doped fibre Amplifiers, differing only in the element of which the fibre is doped and consequently the operating wavelength.

Among the various DFAs in existence, Erbium-doped fibre amplifiers are the most common, most developed and most relevant in terms of optical communication, because of its high gain and broad amplification spectrum (suitable both for c-band, wavelength between 1530 and 1565 nm, and l-band, wavelength between 1565 and 1625 nm).

A specific type of these active fibre, widely used, that have an additional cladding, are the so called double-clad fibres. These fibres have a higher numerical aperture than the ones with single cladding, in which the pump is injected, to be absorbed in the core, as it is illustrated in Figure 3.2.

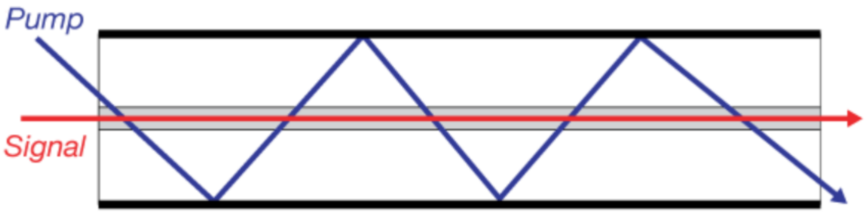


Figure 3.2 – Representation of a double-clad fibre [14]

3.1.1 Erbium Doped Fibre Amplifiers

EDFAs operate at 1550 nm region and can reach a gain of more than 30 dB and low noise of around 3 dB [2].

These amplifiers are essentially made up of Erbium-doped optical fibre (known as active fibre), with a length of up to tens of meters, a pump laser and a photonic component to combine the signal and pump. In these amplifiers, the pump and the signal laser are usually combined using a Wavelength Division Multiplexer (WDM) which is a device that mixes two or more different wavelengths in the same core.

EDFAs are influenced by the length of the Erbium-doped fibre, the wavelength, the pump power and the way in which the wavelength of the signal and the pump are combined. The ideal length of the fibre depends on the pump power and its wavelength, the input power and the constitution of the fibre in terms of the amount of Erbium concentration. Finally, the gain depends on all these factors in addition to the dimensions of the fibre (core radius, numerical aperture, etc.).

The pump lasers in EDFAs (generally in the 980 nm or 1480 nm range) excite the erbium ions in the gain medium to higher energy states. When excited by 980 nm light, the ions first pass through a short-lived state before settling into a metastable state, while excitation with 1480 nm light excites the ions directly into the metastable state. In this metastable state, the ions can store energy temporarily.

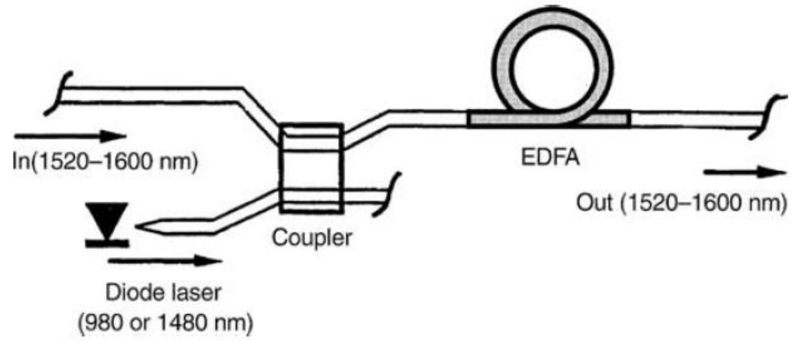


Figure 3.3 —Representation of an EDFA [3]

When a signal with a wavelength of 1550 nm is transmitted—often referred to as a seed signal because it will "grow"—it propagates along the fibre simultaneously with the pump light. As the seed signal interacts with the excited erbium ions in the metastable state, it stimulates them to release their stored energy as photons at the same wavelength and phase as the seed signal. This process, known as stimulated emission, amplifies the seed signal. The amplified light is emitted in the 1525-1565 nm range, corresponding to the transition from the metastable state to the lower-energy ground state. [3].

3.2 Scattering Fibre Amplifiers

These amplifiers use Single Mode Fibre, although the amplification requires a high pump power. The two scattering processes that produce amplification are Stimulated Raman Scattering and Stimulated Brillouin Scattering.

3.2.1 Raman Amplifiers

Raman scattering is intrinsic to any silica glass, due to the characteristics of the material itself. As a result, if a beam is pumped into the fibre and the frequency of the light signal being transmitted along the fibre is similar to the frequency of the pumped light with a small deviation, the initial signal will be amplified. The pumped and the initial signal propagate simultaneously, according to a deviation in wavelength called the Stokes deviation. This deviation is a characteristic of each propagation medium, with the maximum peak corresponding to 100 nm for a pump wavelength of 1450 nm, i.e. the signal would be 1550 nm [4]. These amplifiers are less efficient in terms of power when compared to EDFAs.

3.2.2 Brillouin Amplifiers

Brillouin scattering is an effect caused by a non-linearity of a medium and can occur at low optical power. In a spontaneous process, a photon of incident light is "transformed" into a scattered photon with lower energy and a phonon (a particle that represents the propagation of a disturbance in the structure of a material).

In optical fibres, Brillouin scattering essentially occurs in the opposite direction to the propagation of the beam and can travel tens of kilometres without suffering significant attenuation [5].

Brillouin amplification consists of the propagation of a long laser pulse (pump) which interacts with a short Stokes pulse. These are injected at opposite ends, resulting in an amplified Stokes pulse at the expense of the propagation of the pump pulse, with the direction of propagation of the Stokes pulse [6].

3.3 Fibre Optic Parametric Amplifiers

Parametric optical amplifiers are based on the principles of non-linear optics. A parametric nonlinearity is an interaction in which the quantum state of the material is not affected by the interaction with the optical field.

According to J. Hansryd et al. [7] in these amplifiers, the parametric gain does not depend on energy transitions between electronic states, as it is the case with Raman amplifiers and EDFAs, but instead depends on a process called Four-Photon Mixing (FPM), which relates the phase of the photons that are interacting with each other. These amplifiers can either depend on the phase, called Phase-Sensitive Optical Parametric Amplifier (OPAs), or be insensitive to it, called Phase-Insensitive OPAs. As the Kerr effect depends only on the properties and interactions of the fibre, the gain response time is very short (in the order of femtoseconds), which prevents it from operating in a saturated state.

One of the most significant amplifiers in the context of Parametric Fiber Amplifier (PFAs) is the Stimulated Four-Photon Mixing Amplifier (SFPMA). In this process, two photons from the pump are "absorbed" into a virtual state which then forms two photons, the sum of whose frequencies is equal to twice the frequency of the pump photon, which are propagated in opposite directions. These photons are called Stokes and anti-Stokes wavelengths. As a rule, an SFPMA requires 10 W of pump power to operate [2].

These amplifiers usually have a high gain potential, however they require a complex configuration to maintain an optimal gain.

3.4 Semiconductor Optical Amplifiers

Semiconductor Optical Amplifiers (SOAs) are planar devices based on the same operating principle as semiconductor lasers. These, which consist of a p-n junction, are an excellent light source for optical communication. Electric currents are generated which act as an energy source for the laser, producing a population inversion so that the conduction layer is occupied by electrons, leaving gaps in the valence layer. Thus, when a laser beam passes through the gain medium, the density of charge carriers changes, resulting not only in stimulated emission from the material, but also in a change in the refractive index of the SOA.

There are three different types of semiconductor lasers that can work as optical amplifiers: travelling-wave lasers, Fabry-Perot lasers and injection-locking lasers. The first are those whose light beam passes through the population of charge carriers only once before being amplified; the second, the beam passes through the charge carriers more than once; while the third needs an external signal that will amplify the input, making it more coherent [8].

In general, SOAs have higher noise and lower amplification when compared to fibre optic amplifiers, because they saturate at lower powers than DFAs. However, in addition to their lower cost, they are extremely compact, which is a great advantage [9].

3.5 Hybrid Optical Amplifiers

HOAs are amplifiers that have more than one amplification stage and can be connected in parallel or in series. There are also two types of HOA: Wideband Hybrid Amplifier and Narrowband Hybrid Amplifier. While the former aim to achieve a wider gain wavelength bandwidth and are obtained by combining different optical amplifiers, the latter aim to achieve lower ASE noise and higher gain.

These amplifiers have an enhanced gain across multiple wavelengths once they combine different amplifier types.

3.6 Master Oscillator Power Amplifier

A MOPA is a configuration involving a laser, called a master or seed laser, and an amplifier whose purpose is to increase the system's output power. The first part, the Master Oscillator, generates a signal with certain wavelength or linewidth characteristics, while the second part, the Power Amplifier, considerably increases the output power while maintaining the characteristics of the signal generated by the oscillator.

A Master Oscillator Fibre Amplifier (MOFA) is a specific type of MOPA. Both have a master oscillator and an amplification stage, but a MOFA specifically uses a fibre amplifier and it is involved in a fibre optic system. MOPA is a broader term for various types of amplifiers and applications.

4

TRADE-OFF

A crucial part of this dissertation is the selection of the best option for amplifier. Before simulating and implementing the optical amplifier, it is important to compare the characteristics of each OFA, putting them against the requirements of the project.

4.1 Selection criteria

There is a huge variety of OFAs and the fact that it can be opted for an HOA makes the possibilities even greater, once it is possible to use different OFAs for each of the amplifier stages. Therefore, the first step to take is to define which criteria to take into greater consideration. This initial filtering will not provide the answer, but it will at least direct the study towards certain amplifiers at the expense of others that are not viable. It is important to have always in mind the requirements referred on Section 1, i.e. signal power of at least 6 W, an ER higher than 10 dB and a signal in the 1550 nm range, among others.

4.1.1 Output Power

Although all the criteria are important and naturally must be met, the one that ended up limiting the choice somewhat immediately is the output power. Once the communication depends on this requirement, the inherent characteristics of the fibre used become crucial for the project to achieve the desired results.

The SOAs do not meet this requirement. Although they can have a high gain (~25 dBs), they typically have a maximum output power of 18 dBm (less than 100 mW), which is far from the required values [9]. Although they are an advantage in terms of size and mass, since they are compact optical amplifiers with only a few millimetres long, they do not meet one of the most important points in the development of the amplifier, the output power.

However, precisely because of their spatial characteristics, the possibility of studying the implementation of an HOA with one of its amplification stages being a SOA is not ruled out.

4.1.2 Wavelength

In addition to output power, wavelength is also a limiting parameter. If a signal is to be transmitted along the fibre, it will obviously have to operate at the same wavelength of the signal.

In this context, a laser source with a wavelength of 1550 nm will be used, so the operating region must include this frequency band.

While until now most Rare-Earth Doped Fibre Amplifiers have been a possibility to consider, as they generally meet the fibre length and output power criteria, this is not the case with wavelength.

Of the most widely used Rare-Earth Doped Fibre Amplifiers, only the EDFAs and the Erbium-Ytterbium Co-Doped Fibre Amplifiers (EYDFAs) have a wavelength operating region around 1550 nm. The Ytterbium OFAs have an operating region of around 1000 nm, Praseodymium and Neodymium ones have an operating region of around 1310 nm, while the Thulium ones may have around 800 nm, 1450 nm or 1650 nm [2]. Apart from that, since they have low wavelength noise, it's an advantage to be able to use several channels on a single fibre.

4.1.3 Length of the fibre

The length of the fibre, although not a requirement, has an impact on the amplifier cost budget.

After a survey, on the typical fibre length for each amplifier type and comparing with its cost, the Scattering Fibre Amplifiers, more precisely Raman Amplifiers and Brillouin Amplifiers, and consequently Raman-EDFAs or Brillouin-EDFAs, that usually have a length of several kilometres, are not the best option.

It was conducted a study [10], of how the gain of the HOA varies, considering the length of the optical fibre of the EDFA and the Raman Amplifier. Although, for example, gain values of 40 dB were obtained for a 1530 nm wavelength signal, using 200 mW pump power and EDFA fibre lengths of 15 m, the Raman fibre length is around 25 km.

Despite being the Raman Amplifiers, for example, somewhat common in telecommunications and showing relevant results in the context of this problem, they are more commonly used for long-distance communications.

4.2 Evaluation of Amplifier Options

From the analysis of these selection criteria, it is possible to conclude that, among the amplifiers described in Section 3, the SOAs do not meet the requirement of output power, all doped fibre amplifiers apart from EDFA and EYDFA do not meet the requirement of operating wavelength, Scattering Fibre Amplifiers do not represent the best option because of their length and an HOA would be much more expensive due to its number of amplification stages.

After an initial filtering of the optical amplifiers that can be implemented, it is necessary to check if these amplifiers are capable of meeting the requirements mentioned in this section.

The EDFA is the most relevant option in this context, since it is affordable and easy to implement, has output powers in the order of the desired values and operates in the wavelength region required by the signal.

4.2.1 EDFAs

In telecommunications, the EDFAs are widely used showing results close to those intended for this project. In addition to the fact that some EDFAs have an output power above the desired 6 W, they usually have a bandwidth in the range of 1525-1565 nm and usually have a fibre length of a few meters or a few tens of meters.

In addition to these favourable conditions, EDFAs end up being a simpler and more affordable option than the other options, so it is certainly the most suitable.

4.2.1.1 EDFA as a preamplifier to an EYDFA

It was reported [11] a pulsed laser device consisting only of fibre and suitable for terrestrial communication with satellites, with an output power of 6 W. A seed of 1 mW and 155 Mb/s was used, modulated by a Lithium Niobate Mach-Zehnder Modulator, and then amplified with a gain of 24 dB to 250 mW using a Single-Mode Er-Doped Fibre Preamplifier. Finally, two amplification stages were used with Double-Clad Er-Yb Co-Doped Fibres to achieve the desired 6 W.

In addition to the preamplifier, the booster amplifier and the power amplifier, there are also used insulators to prevent back-propagation between the amplifier stages (which would be detrimental to the system). Additionally, band-pass filters are used to prevent signal propagation between the amplifier stages. All these components are fused together by fibre splice showing passive losses better than 2 dB.

This is, precisely, the kind of system required for the Optical Head, as it has a seed signal that goes through a modulator and then an active fibre, so it is obtained an output power like the one achieved here.

5

SIMULATION

The most effective way to know the best amplifier and/or fibre to use is using a simulation.

The regime of saturation of the output power in respect to the input power is a very important factor to have in consideration when computing the length of the fibre. A gain medium, present in an optical amplifier, cannot maintain a fixed gain for different input powers (seed power). This gain depends on several reasons, being the length of the fibre and the stored energy by the excited ions, two very important factors. So, the gain coefficient can be represented by:

$$g(z,\lambda) = \xi\, N_{dop}\, (\sigma_{21}(\lambda)\, n_2(z) - \sigma_{12}(\lambda)\, n_1(z))$$

where z represents the longitudinal position, λ is the wavelength of the signal, N_{dop} is the doping concentration of the laser-active ions in the fibre core, ξ is an overlap factor regarding how the light travels outside the core, σ is the cross-sections of the transitions between two energy levels in the doped material and n is the population of the two energy levels within the doped material [12].

However, this equation is simplified and does not consider some factors such as parasitic propagation losses and other non-linearities in the fibre and that the pump is constant for each z position. Additionally, the system that it is being developed is dynamic, i.e. a modulated signal needs to be amplified, so, although the static model is important to understand the behaviour of the gain, once the gain of the fibre evolves through time, the dynamic equation for the amplifier gain is much more reliable and can be represented by:

$$\frac{\partial g}{\partial t} = -\frac{g - g_{ss}}{\tau_g} - \frac{g\, P}{E_{sat}}$$

where g represents the logarithmic gain coefficient, g_{ss} represents the small-signal gain, τ_g is the gain relaxation time, P is the power of the amplified beam and E_{sat} represents the saturation energy of the gain medium [13].

Although the development of a simulation tool was foreseen, it was decided to use a commercial simulation tool, that gives much more reliable result in a quite short timeframe.

The OptiSystem software is a quite user-friendly and graphical software that allows the user to define the amplifier simulation using a huge number of parameters, being the most important the fibre length, numerical aperture, core, cladding and double cladding diameter, the shape, signal and pump wavelength and dopant concentration. This software has an extensive library of a large number of different optical and electronic components for fibre and free-space communications, based on realistic models for optical communications systems. Another important feature of this software is the capability to use different models to simulate the system, e.g. it can use a Static Model or a Dynamic Model.

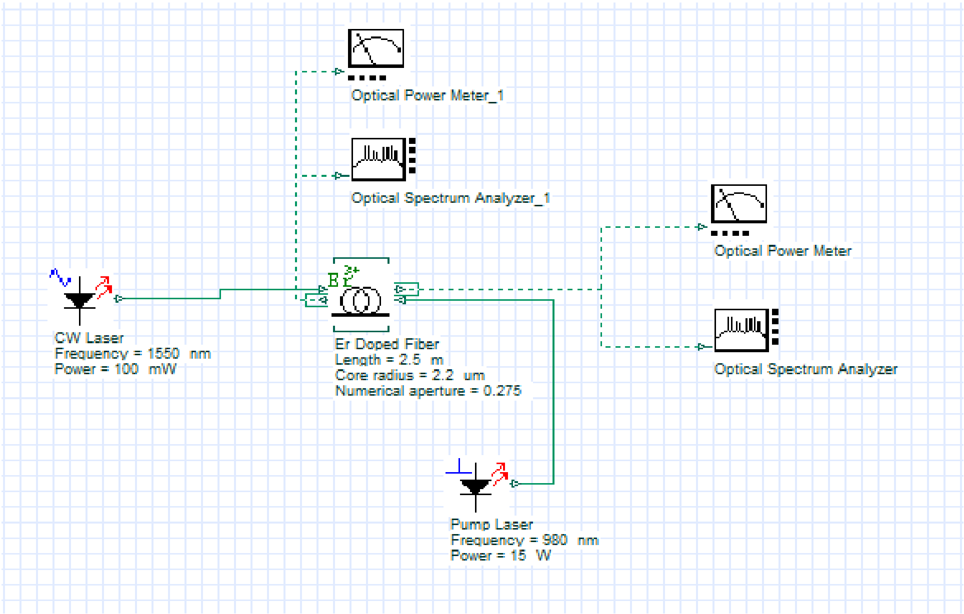
This software turned out to be a very useful tool, with a high level of reliability, that is crucial for the whole project, once it would not be possible to get a more trustworthy tool, already available in useful time.

5.1 Modelling and testing initial conditions

The simulation setup was based on the one that will be implemented and tested in a laboratory environment. The simulation will use a laser source that provides the seed signal to the system, pump lasers, WDMs and/or a pump combiners and doped fibres for amplification. The system characterization was done using Optical Spectrum Analysers (OSA), power meters, fast detectors and oscilloscopes to analyse the signals that are transmitted forward and those that return backwards. Figure 5.1 shows an image of the experimental apparatus in the OptiSystem environment.

To perform the simulation in order to fine tune the pump power, numeric aperture and fibre length, these values were varied for different seed power values. The results were recorded for each configuration in order to optimise each parameter. With this method it was possible to understand the parameters influence on the output power of the system. The results obtained are in the Appendix A.

With these results a market survey on active fibre that could match the desired values was done. For that it was selected some suppliers, mainly the ones that have a low lead time, such as Thorlabs, iXblue, Coherent and Fujikura.



CW Laser
Frequency = 1550 nm
Power = 100 mW

Er Doped Fiber
Length = 2.5 m
Core radius = 2.2 um
Numerical aperture = 0.275

Pump Laser
Frequency = 980 nm
Power = 15 W

Figure 5.1 —Example of a simulation in OptiSystem

5.2 Defining the simulation

For the validation of specific optical fibres, the same model was used for all of them. It was only recorded the values for an input power of 1 mW and for 100 mW, since it was intended to understand the output values obtained when the emitter is "off" and "on" (simulating the modulation signal with an ER of 20 dB).

It is well-known that, for a non-saturated state of the fibre, the higher the seed power, the higher the output power. Contrary, in a saturation regime, the seed power will not influence the output as it is in linear regime. However, the goal is to have the lowest pump power possible, ideally less than 15/20 W.

The study and evaluation of output power therefore ideally consisted of obtaining the lowest possible output value and the highest backscattering value for signal "0", i.e. with 1 mW of seed power, and 6 W of output for signal "1", i.e. 100 mW of seed power. By obtaining a minimum value when the seed is off and a maximum value when it is on, the ER is maximized. One of the objectives is to have an ER, that is a ratio between the value of the signal when it is on and when it is off, of around 12 dB, which is equivalent to a difference of around 15 times. Note that an ER of higher than 10 dB is necessary for the satellite to distinguish innocuously between when the signal is on and when it is off, although lower ER can be handled by the satellite, depending on the signal quality (e.g. wavefront) and its receiving system (e.g. telescope, detector, electronics, etc..).

In respect to the study of the output power, the backscattered power is also a crucial parameter to be aware of, in order to protect the amplifier and lasers, as the backscattered power should be, typically, less than 10 W.

5.3 Simulation results

Once the different optical fibres from different suppliers were selected, their length, numerical aperture and core radius were collected in order to introduce these characteristics into the simulation.

The output and backscattered power values were recorded for each selected fibres, using the pump and seed power values mentioned above. Since these simulations are no longer being carried out with hypothetical fibres, the only parameter that can be changed is the length of each fibre. All other parameters were given by the supplier datasheet. Table 5.1 represents the fibres that achieved a value of output power and ER according to the requirements. The achieved results for all the fibres simulated are shown in Appendix B.

Optical Fibre	Seed Wavelength (nm)	Input Power (mW)	Pump Wavelength (nm)	Pump Power (W)	Fibre Length (m)	Output Power (W)	Extinction Ratio (dB)
SM-ESF-7/125	1550	1	980	15	4,25	0,455036	11,329
		100				6,180	
		1			4,5	0,630269	10,224
		100				6,636	
Er30-4/125	1550	1	980	15	3	0,629800	10,246
		100				6,665	
EDFL-980-HP	1550	1	980	15	2,75	0,497584	10,992
		100				6,252	
EDFL-1480-HP	1550	1	980	15	2,5	0,616575	10,048
		100				6,234	
PM-ESF-7/125	1550	1	980	15	4,5	0,514769	10,884
		100				6,310	
EDFC-980-HP-80	1550	1	980	15	2,75	0,526759	10,801
		100				6,335	
EDFH0790	1550	1	980	15	3	0,526433	10,921
		100				6,508	
EDFH0790	1550	1	980	15	2,75	0,497595	10,991
		100				6,252	
SCF-ER-6/125-14	1550	1	980	15	4,5	0,561904	10,810
		100				6,771	
SMF-28 Ultra 200 Optical Fiber	1550	1	980	15	5	0,438004	11,422
		100				6,077	
		1			5,25	0,577586	10,492
		100				6,468	
Er16-8/125	1550	1	980	15	5,5	0,565655	10,639
		100				6,553	

Table 5.1 —Simulation results of fibres from different suppliers

The purpose of this simulation was to select the potential fibres to be used, since the vast majority, as can be seen from the results of Appendix B, end up not achieving the desired values. This minority was selected by having achieved values of output power, when the transmission is on, i.e. 6 W and by having an ER of higher than 10 dB. Finally, the choice of the active fibre to be used was based on the available budget for this task and the predicted time delivery of the fibre. Thus, it was selected the Thorlabs Er16-8/125 active fibre.

6

PRELIMINARY TESTS

Once the simulation had been carried out and the fibre selected, it was decided to validate the simulation experimentally. So, the next stage was to assemble the amplifier according to the simulation, including all the necessary components and instruments, in the optics laboratory, inside an ISO-8 class clean room. Lusospace has two large clean rooms, one ISO-5 and one ISO-8, where almost all optical tests are carried out, which makes this space perfect for these tests. In addition, all the necessary instruments and photonics, such as polarisers, insulators, combiners, etc. are stored in this room, which is an advantage when, during tests, some components need to be replaced.

6.1 Simulation validation

As it was referred, several simulations were done using an Er16-8/125 active fibre. However, other simulations, identical to the previous ones, were also performed using 1064 nm wavelength. This was done because Lusospace had Ytterbium and Erbium active fibres available that could be used to test and validate the simulation.

The aim of this phase was to see what results the simulated amplifier assembled in the laboratory could produce.

6.1.1 Ytterbium OFA

According to the simulations and as illustrated in Figure 6.1, it was assembled a 1064 nm OFA.

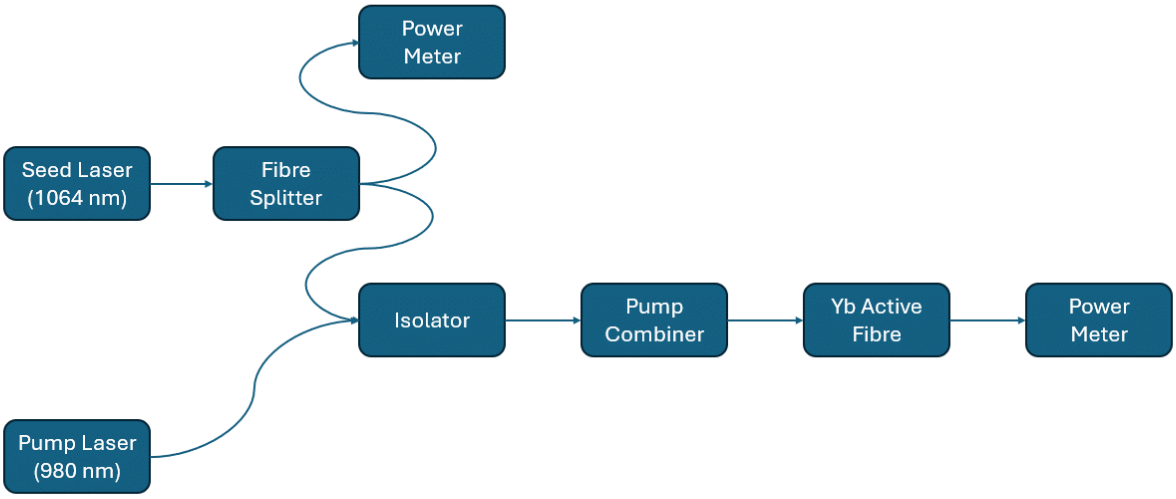


Figure 6.1 — Assembly of the test with a 1064 nm laser and Ytterbium fibre

This amplifier uses a pump combiner, once it is used a double cladding fibre, a splitter to monitor the seed power and an insulator just before the pump combiner for protection. All fibres connections between components were done using splices.

The fibre splitter is used to split the beam coming from the signal into two components. In this case it was used 75:25, being the higher output used for the amplifier and the lower output for monitoring. The pump combiner is a crucial component that introduces the pump in the fibre (inner cladding) so that the two can be propagated along the active fibre.

Once the amplifier was assembled with the monitoring instruments properly placed to obtain the results, it was acquired the output power, pump power, pump laser current, seed power and seed laser current, for both a fibre with 1,5 meters of length and another with 3,5 meters. It was selected those fibre lengths since they were the available ones. These results are presented in Table 6.1 and in more detail in Appendix C.

Seed Power (mW)	Pump Power (mW)	Output Power (mW)	Fibre Length (m)
4,5	500,914	10	1,5
	1004,097	22	
90	500,914	112	
	1004,097	150	

Seed Power (mW)	Pump Power (mW)	Output Power (mW)	Fibre Length (m)
1,2	500,914	42	3,5
	1004,097	280	
4,5	500,914	103	
	1004,097	365	
90	500,914	303	
	1004,097	628	

Table 6.1 — Results of the test for an Ytterbium fibre with 1,5 and 3,5 metres length

With these results, it can be seen that the length of the fibre influences greatly the results of the output power, which represent a very important factor in the context of this study, to understand the system behaviour, and what to expect when assembling a system like this one.

6.1.2 Erbium OFA

For the tests using the 1550 nm wavelength, it was used an Erbium active fibre, as illustrated in Figure 6.2.

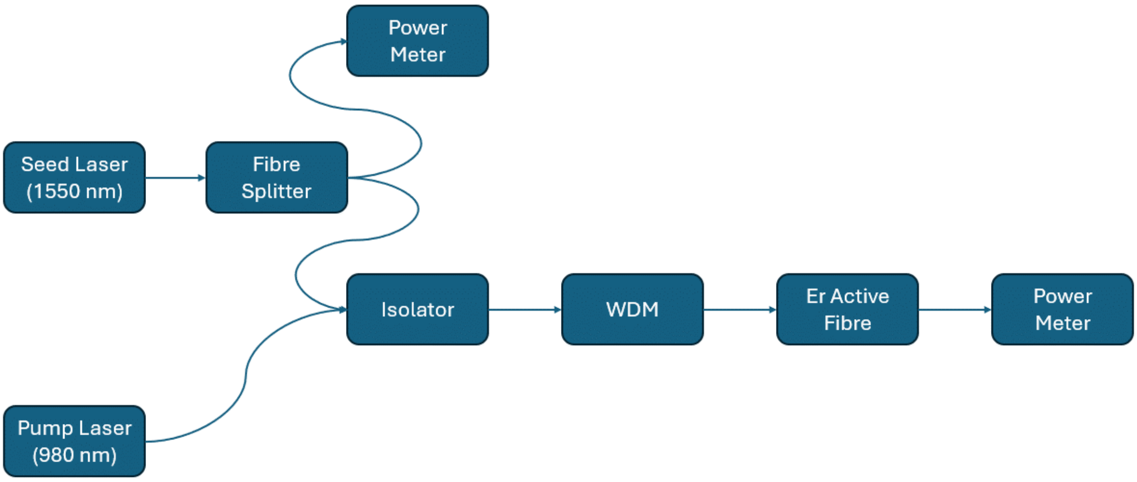


Figure 6.2 — Assembly of the test with the 1550 nm laser and Erbium fibre

Similar tests to the Ytterbium OF were done using the EDFA amplifier showing consistent results when comparing to the simulation.

However, during the simulation of the EDFA, a challenge was raised. The COTS WDMs do not withstand more than 5W. Once it was required a double cladding fibre, due to the involved high power, and since it would not be possible to use WDMs, it was started the process of market survey on a double cladding Erbium fibre.

However, the Er16-8/125 fibre, as all the Erbium doped fibres, has a single cladding. That means that when the light passes through the fibre, both the signal laser and the pumped laser travel through the core with the respective wavelengths. The problem consists of the fact that the pump combiners, as the one used in the assembly, when receiving the signal laser and the pump laser, do not emit them both in the core of the fibre. Rather makes the signal beam travel through the core and the pumped beam travel through the cladding. Thus, this requires double cladding fibre, with the outer cladding serving as a block, avoiding the pump light to exit its means of propagation.

This said, either the already finished study of the Erbium doped fibre must be reformulated to be done with another fibre, or the assembly of the system has to change to go towards the requirements of the Er16-8/125 fibre.

6.2 Active Fiber Selection and simulation

After some research and having in mind the thought process of Section 4, it was realized that the Erbium-Ytterbium Co-Doped Fibres have similar results to the Erbium Doped Fibres. An EYDFA requires almost the same parameters of an EDFA (such as operating bandwidth, length or core radius) and it is constituted with a fibre with double cladding, enabling a system with a pump combiner, so allowing to use much higher power.

This said, the Erbium-Ytterbium OFA was decided to be the selected to be used as the optical head amplifier in the transmission channel.

6.3 EYDFA simulation

The aim of this simulation was to define what length should be used for a minimum output of 6 W and 10 dB ER.

Since the simulation uses the dynamic model, which is extremely time-consuming, several simulations were carried out using the static model to verify the length effect. Figure 6.3 shows the simulation for a fibre with a length of 5 m.

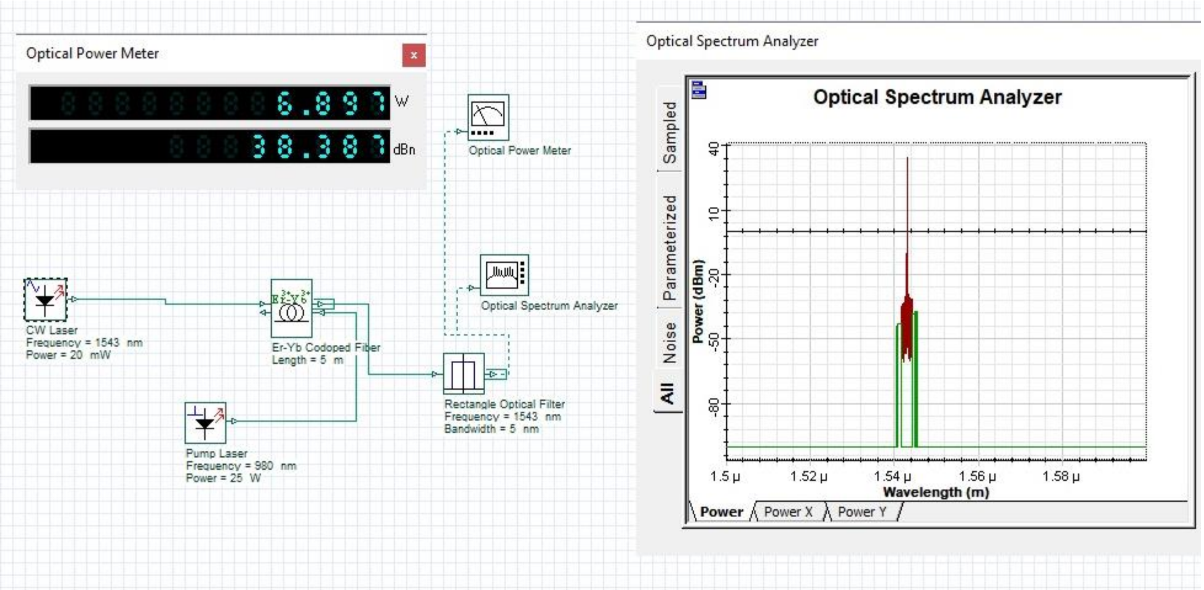


Figure 6.3 —Simulation of the static model for an Er-Yb fibre with 5 metres length, in conditions similar to the ones that will be done in laboratory ambience; Representation of the values recorded by the Optical Power Meter (left) and the Optical Spectrum Analyser (right)

It should be noted that other parameters that influence the simulation were adjusted, such as the diameter of the double-cladding, the diameter of the core, the absorption, among others. These values were based on the parameters of a fibre previously selected mainly due to its delivery time, which was an important factor in its choice. The main parameters used are represented in Table 6.2.

Core Radius	5 µm
Numerical Aperture	0.1
Signal loss	1 dB/m
Pump loss	1 dB/m
Inner Cladding Area	12000 µm^2
Length	1 - 6 m

Table 6.2 —Parameters used for the fibre of the simulation in Figure 6.3

Keeping the parameters from Table 6.2 constant, it was scanned the lengths from 1 to 6 metres, obtaining the graphic from Figure 6.4.

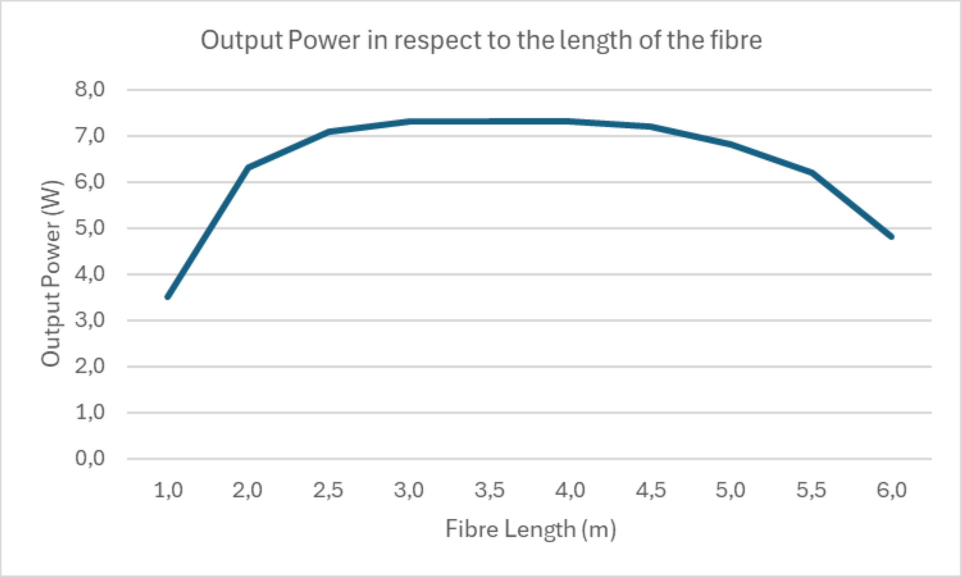


Figure 6.4 —Graphic of the output power in respect to the length of the fibre, obtained with the simulation from Figure 6.3, for a fibre with the parameters listed in Table 6.2

After the simulation using the static model, simulations were carried out using the dynamic model with a signal at a frequency of 1 GHz in order to check the ER. The results of the simulations are represented in Figure 6.6 and show a high ER, i.e. well over 10 dB, which is quite important. It should be noted that this ER value is only indicative and will end up having a large error when compared to the experimental value, since the simulation used an ideal modulator.

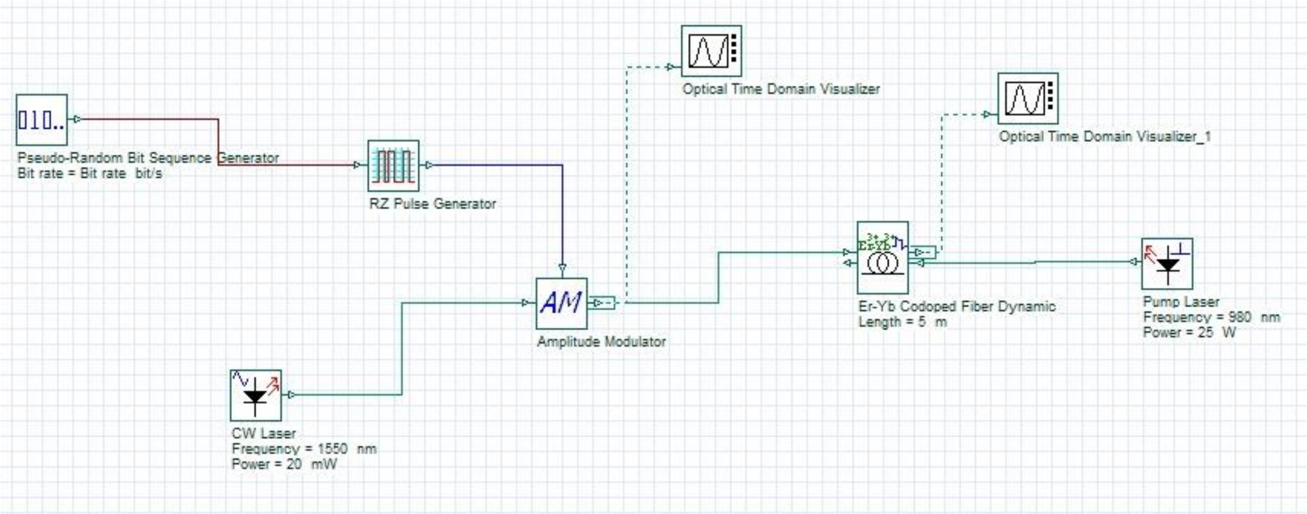
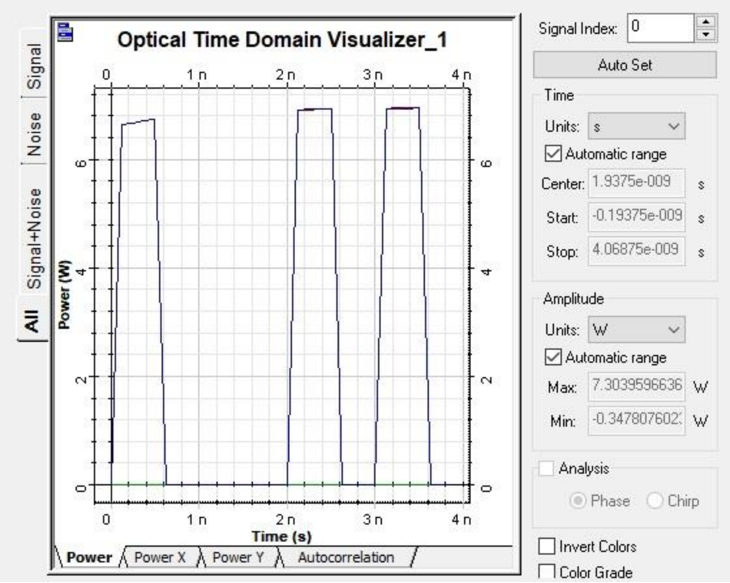


Figure 6.5 —Simulation of the dynamic model for a Er-Yb fibre with 5 metres length, in conditions similar to the ones that will be done in laboratory ambience



Signal Index: 0

Time
Units: s
☑ Automatic range
Center: 1.9375e-009 s
Start: -0.19375e-009 s
Stop: 4.06875e-009 s

Amplitude
Units: W
☑ Automatic range
Max: 7.3039596636 W
Min: -0.347807602: W

☐ Analysis
○ Phase ○ Chirp

☐ Invert Colors
☐ Color Grade

Figure 6.6 —Representation of the output power in respect to time; It can be noted a output power of more than 6W and a ER of more than 10 dB

With these results, it can be concluded that the selected Erbium-Ytterbium OFA meets the requirements with very satisfactory results for a 5-metre-long fibre, making it possible to define the final assembly. After a similar survey to that carried out for the previously researched erbium active fibre, iXblue's IXF-2CF-EY-O-10-130-0.10 was acquired.

7

FINAL ASSEMBLY

With all the different tests and simulations of the system described in previous sections and with a 5-metres Er/Yb-doped active fibre purchased from iXblue, it was finally possible to define the assembly of the OFA, which will be explained in more detail in this section.

This setup goes according to what it is supposed to have in the Optical Head, has a behaviour like the one in the previous simulations and it is similar to other results found in the literature. However, it is important to note that the results obtained in the simulations are ideal and the final results of the tests will not be exactly the same as those from the simulations.

7.1 Amplifier's architecture

The overall amplifier architecture based on the described simulation is presented in Figure 7.1.

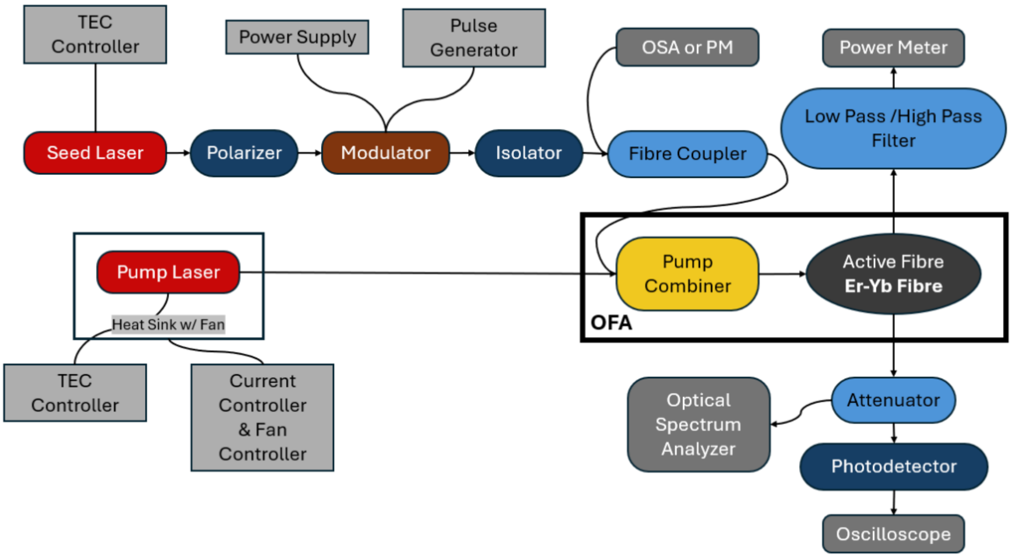


Figure 7.1 —Scheme of the system and the OFA

The setup is composed by the pump laser and the seed laser (represented in red), the modulator (in brown), the pump combiner (in yellow), the active fibre (in black) and by the fibre coupler, filters and attenuator (in cyan) used to condition or extract the signal, allowing its measurement. All power supplies and devices controllers are represented in light grey, while the detection equipment is represented in dark grey.

The seed laser emits a signal that passes through the polarizer. This device is used to maintain the polarization fixed (linear polarization aligned with the power meter fibre slow axis), once the laser changes slightly its polarization orientation over time, with temperature fluctuations. This is quite important since one of the requirements is the ER and the modulator performance depends on the polarization orientation.

After the modulator, there is an insulator to prevent that the back-propagated light, which can be a few Watts, goes into the modulator, polarizer and laser. Nevertheless, this signal can be monitored through the coupler placed right after.

The pump combiner makes the pump laser signal travel in the inner cladding of the fibre, while the seed signal travels in the core. Finally, the active fibre amplifies the signal, that can be directly detected by the power meter or, using the attenuator, by the fast photodetector and oscilloscope or even by the OSA.

In the next section, the final amplifier is presented, including all photonic parts.

7.2 Amplifier implementation

Following the presented architecture, the overall amplifier was assembled as it can be seen in Figure 7.2.

The assembly is composed by the seed laser (represented in 1), the pump laser (represented by 2 along with its high power cooling interface), the modulator (3), the pump combiner (4), an active fibre (5), a fast photodetector (6), a polarizer (7), the insulator (8), a free-space setup that includes a lens setup, and a pinhole working as an attenuator (9), a power meter (represented by 10), an optical spectrum analyser (represented by 11) and an oscilloscope (not showed). The attenuator is extremely important when high power signals need to be measured. Note that both fast photodetector and OSA can only handle 1 mW.

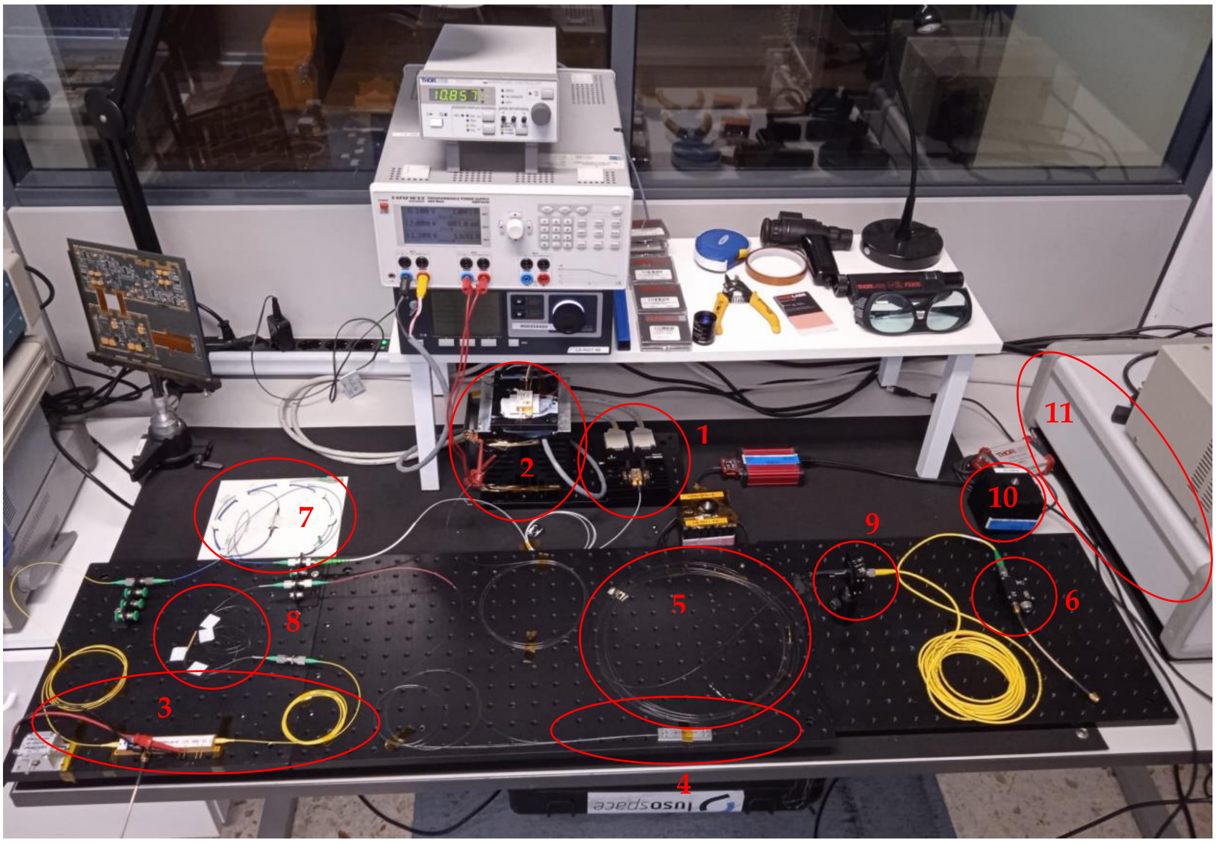


Figure 7.2 —Final assembly. 1. seed laser; 2. pump laser; 3. modulator; 4. pump combiner; 5. Er-Yb active fibre; 6. fast photodetector; 7. polarizer; 8. insulator; 9. attenuator; 10. power meter; 11. OSA

7.3 Safety

Since lasers are being used, mainly high-power lasers with several Watts, various protective barriers must be used, both administrative and physical. It should be noted that in this case, in addition to the power used, the light is not visible to human eyes, which increases the danger.

The administrative barriers refer to the signs that have been put up inside and outside the laboratory, warning that high-powered lasers are operating inside the laboratory, as well as an email message mentioning the same.

As far as physical barriers are concerned, laser goggles with OD6+ for the 1550 nm range were made available and mandatory, and several black aluminium sheets were used to cover the entire installation, especially the high-power areas (pump and outlet). In addition, an infrared viewer (Thorlabs VWR2B) was used to check for any visible fibre leakage or reflections.

8

RESULTS AND DISCUSSION

The last stage of this dissertation was to perform the amplifier characterization and to determine in which conditions do the better results stand out.

The parameters that were used to characterise the fibre were the output power, the ER and the falling and rising time, the operating wavelength bandwidth, the residual pump power and the power of the signal that was backpropagated.

As it will be explained in the next sections, it was registered values for a length of 5,5 m and a length of 5 m (although it was ordered 5 m, it was delivered a fibre with 6 m). Once it turned out to be used only 5,5 m, due to the splices that were done, including the ones used to fine tune the splicing machine (it is needed around 4 cm of fibre for each splice), it was not possible to verify the results for a greater length than 5,5 metres. The minimum value of length of the fibre registered was 5 m, once (as it will be explained) the results started to get unsatisfactory.

Some of the results obtained are showed in Appendix E. The process to get these values, as well as a brief description and analysis to the results is described in this section.

8.1 Output Power

As it was briefly explained in Section 7, a power meter is used to measure the output power of the OFA. The face end of the fibre is placed pointing towards the centre of the power meter, using the high pass filter. The power meter is an integrated sphere allowing the high-power detection without using an attenuator, being the energy collected by the photodetector a ratio between the sphere surface and the photodetector sensitive area. The use of the high pass filter is needed to measure only the signal power, since no cladding stripper was used to remove the residual pump power. The power meter is then connected to a computer to observe the results using the Thorlabs Optical Power Monitor software. These results were obtained without the modulation of the signal.

Thus, the output power value was recorded for both a 5-metres length and a 5,5-metres length of fibre. As it can be seen in Figures 8.1 and 8.2 (and in more detail in Appendix E.1), the output power for the 5 m fibre was nearly 1,5 W, while the fibre with 5,5 m reached almost 3 W, for the same a pump power of 13 W.

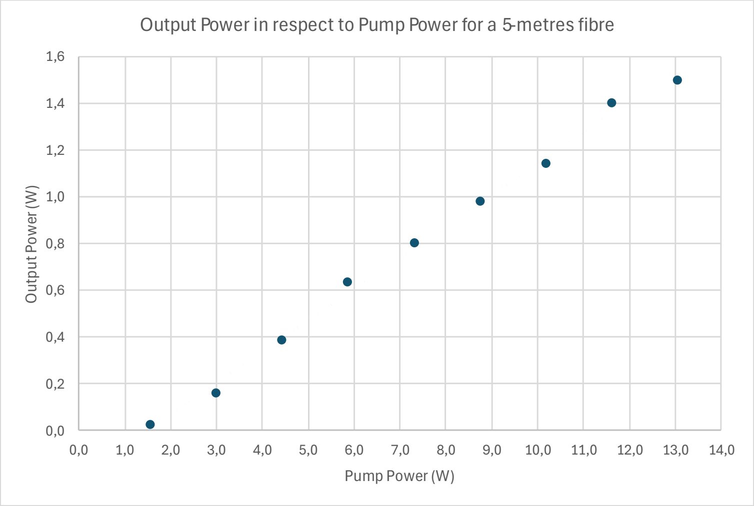


Figure 8.1 —Graphic of the evolution of the output power in respect to pump power for a 5-metres fibre

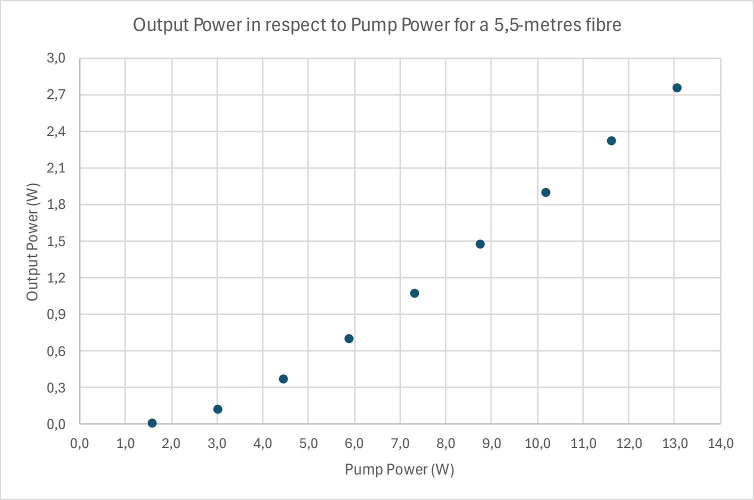


Figure 8.2 —Graphic of the evolution of the output power in respect to pump power for a 5,5-metres fibre

The gain is lower for the 5 m long fibre than for the 5,5 m, i.e. for a signal of 20 mW and 13 W pump, the output was 1,5 W for the 5 m fibre and 2,7 W for the 5,5 m, which means that a gain of $10 * \log\frac{1,5}{0,001} \sim 22\ dB$ and $10 * \log\frac{2,7}{0,001} \sim 24\ dB$ were obtained, respectively.

The above measurements were only carried out for an output power of 2.7 W because the insulator used (it was the only one available for 1550 nm) could only handle less than 1 W. To measure the maximum output power, the pump power was increased using larger steps, in order to carry out the measurement as quickly as possible, reducing the energy absorbed by the insulator.

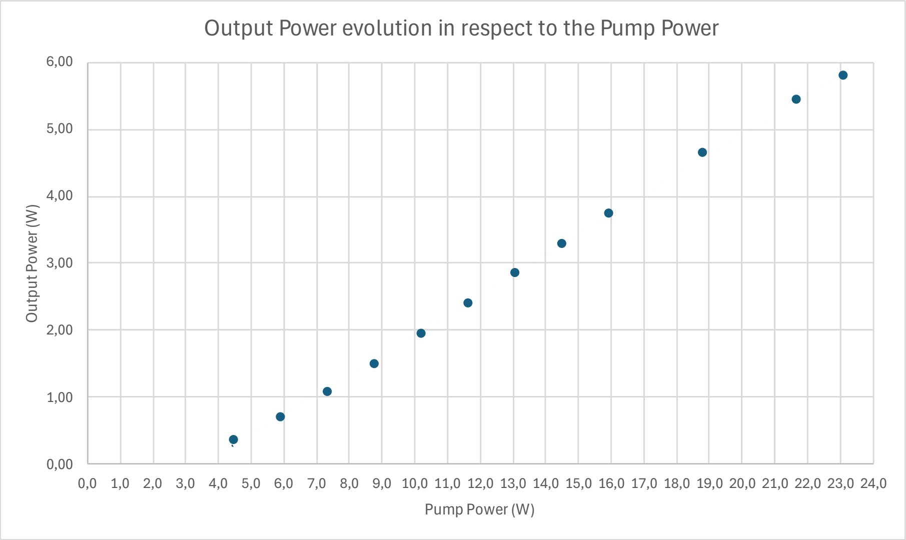


Figure 8.3 —Graphic of the final results of the output power in respect to pump power for a 5,5-metres fibre

According to the graphic of Figure 8.3, the fact that only 5,5 m of active fibre was used, limited the output power to 5,8 W. Although the data indicates that the output power depends linearly on the pump power and does not appear to have a curve for the highest output power values in Figure 8.3 (which would indicate the start of the saturation regime), the pump power was increased by a step above 23 W and did not seem to significantly influence the output power. However, these higher values were not recorded for safety reasons.

Although the objective was to achieve 6 W, once using 5,5 m allowed us to achieve good results, one can conclude that the 6 W would be achieved if a slightly longer fibre was used. It is important to refer that the pump laser was previously tunned, i.e., it was performed a temperature scan between 15 ºC and 40 ºC while measuring the output. As a result, it was achieved the temperature of 20 ºC for the highest output value. The temperature was used for all tests.

8.2 Extinction Ratio

To measure the ER of the signal, a fast detector must be used, thus, the attenuator device is needed once a photodetector is used to detect the signal that will be measured using the oscilloscope. The developed attenuator is illustrated in Figure 8.4.

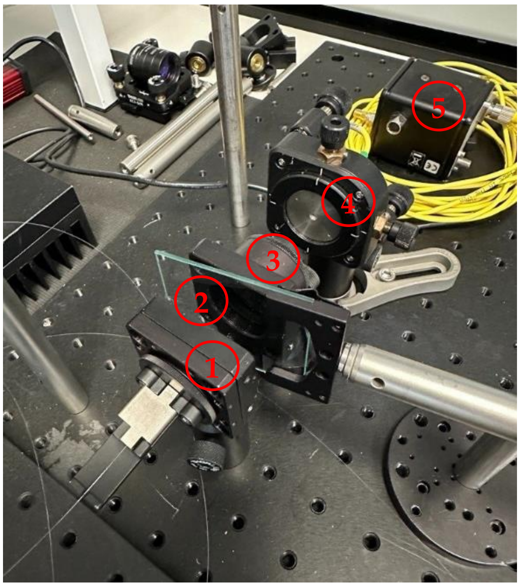


Figure 8.4 — Free-space attenuator to reduce the power to a few hundreds of µW to be safe to measure with the fast photodetector and OSA.
1. bare fiber holder; 2. neutral filter (OD1); 3. focusing lens; 4. FC/APC fibre holder; 5. photodetector

This attenuator, basically, consists of a lens after the face-end of the fibre to focus the beam on a 10-µm core fibre which is connected to the fast detector or OSA. The attenuation value can be selected by focusing/defocusing the beam on the core. An additional neutral filter was also used to attenuate the power before the lens. Note that this setup was always covered by an aluminium foil for safety reasons.

The use of an oscilloscope with a high bandwidth (25 GHz) is essential to characterize signals with GHz frequency.

The minimum and maximum output power after the modulation were registered, from which the ER could be calculated. These values cannot be compared to the recorded with the power meter because of the use of an attenuator. Nevertheless, the ER is calculated by $ER = 10 \cdot LOG({}^{P_{max}}/_{P_{min}})$, meaning that only relative values are needed. Note that to achieve high ER, the P_{min} should be as low as possible. Figure 8.5 illustrates the results obtained for both fibres length.

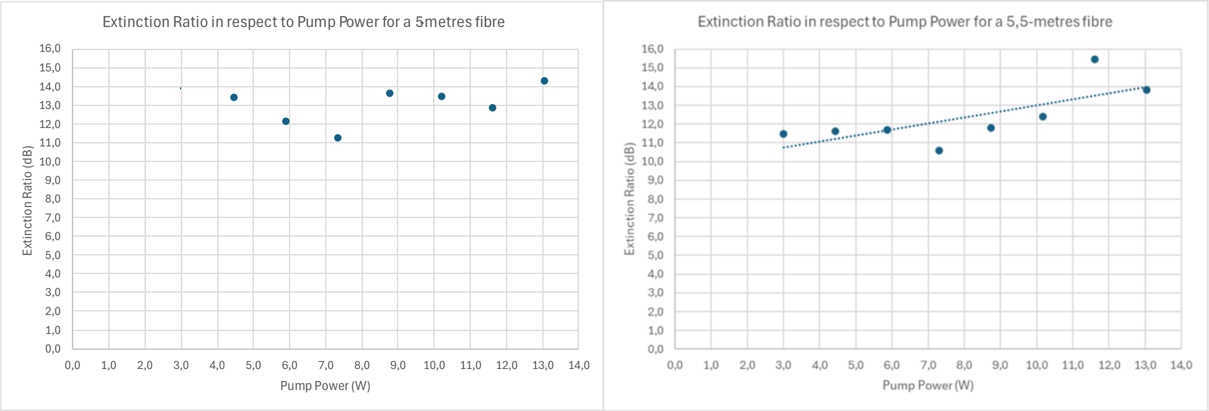


Figure 8.5 — Graphics of the ER in respect to pump power for a 5-metres fibre and a 5,5-metres fibre

The achieved results for both fibres are in line with the requirement that was to be "higher than 10 dB".

However, the difference of around 3 dB in ER (a significant value, not to be ignored) that was registered between measurements, was due to the modulator half-wave-voltage offset slightly changing over time leading to a fluctuation mainly on the P_{min} value. Note that this system usually has an auto bias setup, assuring that the modulator bias is optimized.

8.3 Operating wavelength bandwidth

To measure the operating wavelength quality, the same attenuator setup was used. In fact, it was only needed to disconnect the fibre from the fast photodetector and connect it to the OSA. This instrument measures and analyses the power distribution of the optical source over a specified range of wavelengths. The data is acquired and analysed using a computer using the ThorSpectra software from Thorlabs.

Figure 8.6 represents the distribution in wavelength of the output power when the pump power is 7,3 W.

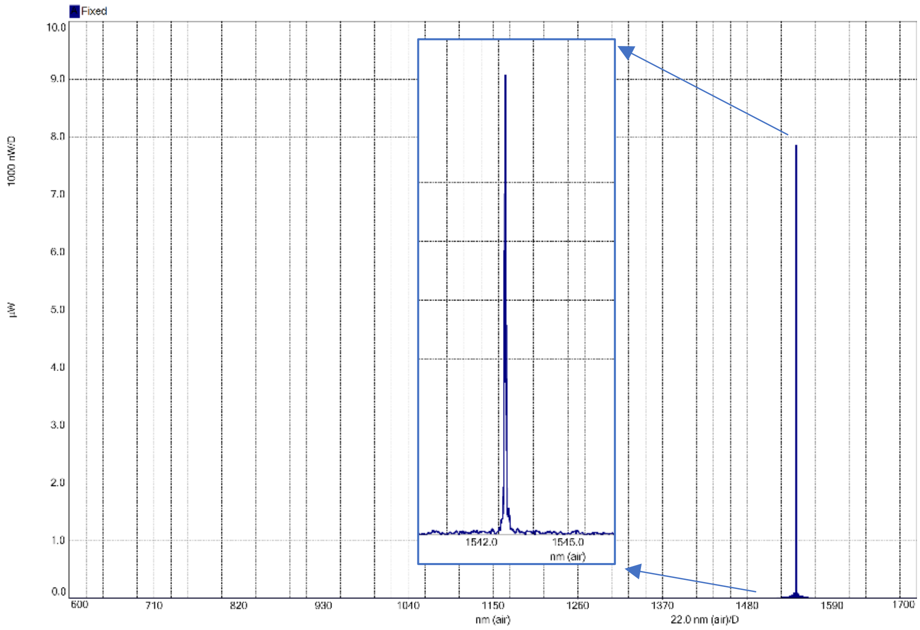


Figure 8.6 —Distribution in wavelength of the signal of the output power for a pump of 7,3 W

This result shows a quite narrow linewidth centered at approximately 1543 nm, i.e. the wavelength of the seed signal.

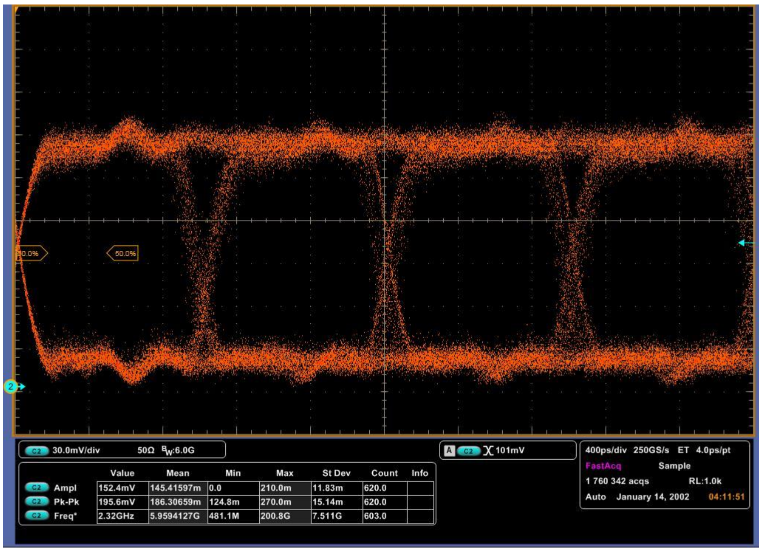
In Appendix E.3, it can be found other information, obtained with OSA, showing relevant results for this parameter.

8.4 Rise and fall time

A crucial feature for the communication between the aircraft and the satellite is the time it takes between the transmission being on and off. For this, it was also used the oscilloscope and the photodetector to take these measures.

The setup is the same as for the ER, being the only difference in the representation of the signal in respect to time. For the visualization of this parameter, the most common method is by analysing the eye diagram, i.e. repeatedly overlaying the samples over several-bits periods.

These values were obtained for two different frequencies of modulation, of 500 MHz (1 Gb/s) and 1 GHz (2 Gb/s). The time between the on/off connection was of around 250 ps for both frequencies. The eye diagrams that allow the analysis of this parameter are represented in Appendix E.4 and in Figure 8.7.



C2 30.0mV/div 50Ω B_W:6.0G

A C2 ⨯ 101mV

400ps/div 250GS/s ET 4.0ps/pt
FastAcq Sample
1 760 342 acqs RL:1.0k
Auto January 14, 2002 04:11:51

	Value	Mean	Min	Max	St Dev	Count	Info
C2 Ampl	152.4mV	145.41597m	0.0	210.0m	11.83m	620.0	
C2 Pk-Pk	195.6mV	186.30659m	124.8m	270.0m	15.14m	620.0	
C2 Freq*	2.32GHz	5.9594127G	481.1M	200.8G	7.511G	603.0	

Figure 8.7 —Eye diagram for a frequency of 1 Gb/s and a pump power of above 10 W

8.5 Residual pump power

For the residual pump power measurement, the setup was identical to the one of the output power. The only difference was the used filter placed before the power meter. While for the output power it was used a high-pass filter, that allows to measure wavelengths above 1400 nm, for the residual pump power a low-pass filter to measure wavelengths below 1000 nm was used. Note that the wavelength of the pump's residual power would be around 980 nm (the same as that of the pump).

Similarly to the output power, the residual pump power was characterized as a function of the pump power for a maximum pump of 13.1 W.

Although it wasn't possible to carry out the test for higher values of pump power, the graphics in Figure 8.8 show that the residual pump power increases with the pump power, as it would be expected. This eventually leads to a point where the output power does not increase, causing the fibre to saturate and no longer being able to amplify the seed signal.

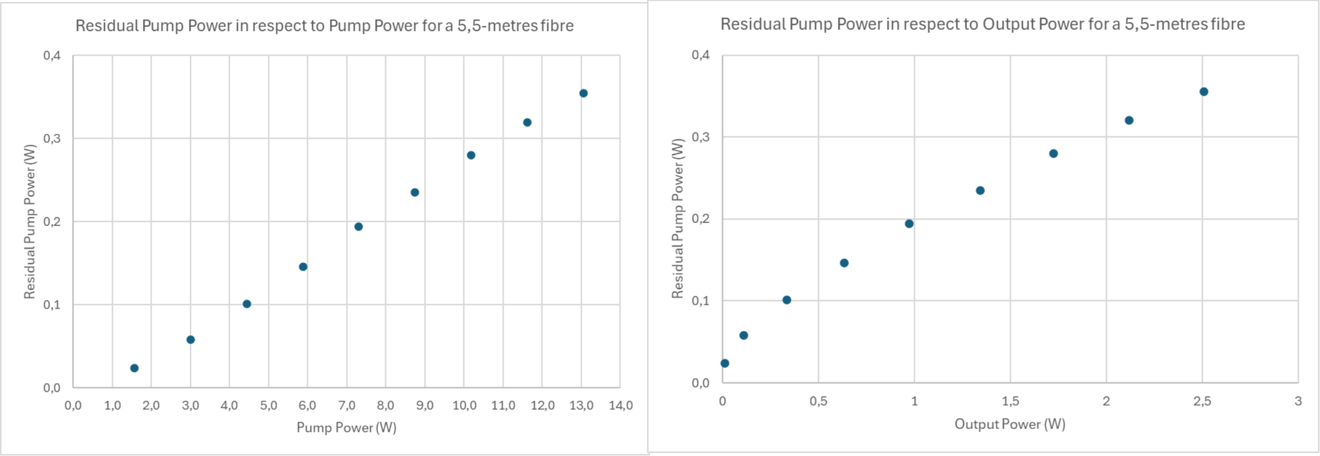


Figure 8.8 —Graphics of the residual pump power in respect to the pump power and to the output power for a 5,5-metres fibre

8.6 Backpropagated Optical Power

To measure the portion of light that is backpropagated, it was used a fibre coupler, component that was not part of the previous tests. It was added a 2x2 fibre coupler (its specifications are presented in Appendix D) allowing to monitor the light that travels in both directions.

This fibre coupler (Figure 8.9) has two fibre branches on each side, dividing the light from one of the branches on side A into the two on side B by a factor of 10/90. The fibre coupler was placed between the insulator and the pump combiner. The goal of this setup was to monitor the optical power that the active fibre effectively amplifies in the backward direction.

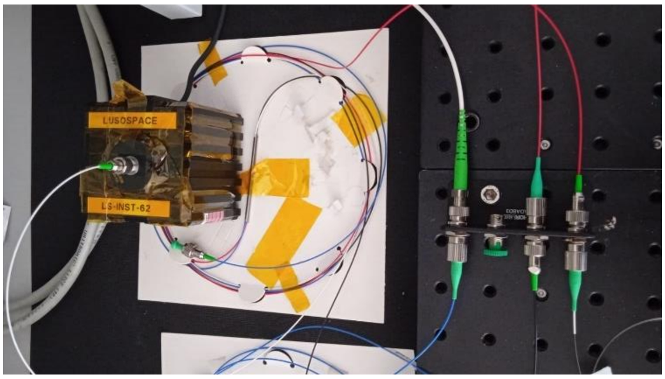
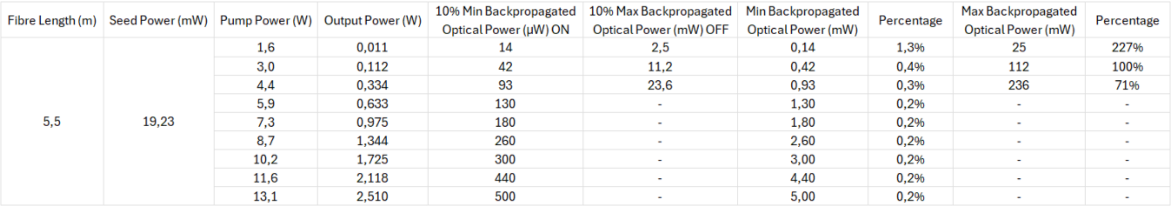


Figure 8.9 —Fibre Coupler

The values were recorded for signal "on" and "off" and it was observed that the higher value of the backpropagated output power is achieved when the seed signal is "off" and the lower value for when it is "on", as expected. These values are presented in Table 8.1.



Fibre Length (m)	Seed Power (mW)	Pump Power (W)	Output Power (W)	10% Min Backpropagated Optical Power (µW) ON	10% Max Backpropagated Optical Power (mW) OFF	Min Backpropagated Optical Power (mW)	Percentage	Max Backpropagated Optical Power (mW)	Percentage
5,5	19,23	1,6	0,011	14	2,5	0,14	1,3%	25	227%
		3,0	0,112	42	11,2	0,42	0,4%	112	100%
		4,4	0,334	93	23,6	0,93	0,3%	236	71%
		5,9	0,633	130	-	1,30	0,2%	-	-
		7,3	0,975	180	-	1,80	0,2%	-	-
		8,7	1,344	260	-	2,60	0,2%	-	-
		10,2	1,725	300	-	3,00	0,2%	-	-
		11,6	2,118	440	-	4,40	0,2%	-	-
		13,1	2,510	500	-	5,00	0,2%	-	-

Table 8.1 —Results of the backscattered output power

Comparing the values between the backpropagated output power and the output power, it is possible to understand how the propagation of the light from the active fibre behaves. When the transmission is "on", the backpropagated output power is nearly insignificant compared with the actual output power, being 5 mW when the output power is above 2,5 W, something that represents less than 0,2%. When the transmission is "off", the backpropagated output power is practically the same as the actual output power, being 236 mW when the output power is 334 mW, representing more than 70%.

It was not possible to register values for when the transmission is "off" with the pump power being above 4,5 W, because with a higher pump power, the values of backpropagated output power would be even higher and that power would damage the insulator. This problem does not remain for other tests (for example the test of the ER) because in that case, the transmission power varies quite fast between the "on" and "off" state (GHz frequency), which means that the insulator did not have to sustain for a long time the backpropagated output power.

The columns of the table corresponding to the "10% Min/Max Backpropagated Optical Power" concern the values that are recorded in the power meter after the fibre coupler. Since only 10% of the output power that travelled in the backward direction is measured at the power meter, 90% will go to the insulator. So, to register the value of the minimum or the maximum backscattered output power, the previous values must be multiplied by 10.

These results indicate that most of the light amplified by the active fibre is travelling in a forward direction, as it is intended.

9

CONCLUSION

In summary, this project could be divided into several steps: understanding the functioning of an OFA, searching for the best OFA to implement in this project, assembling and testing. Finally, it was done a data processing and analysis to characterise the OFA.

After all the results were taken and the analysis completed, it is concluded that this project went according to the expectations set by Lusospace. It was possible to find a solution for the OFA that fulfils the requirements set as objectives.

Different OFA parameters were measured, such as the optical output power, ER, wavelength linewidth, residual pump power and the backpropagated, where the most important data was the optical output and the ER values. As a result, it can be concluded that an Er-Yb co-doped fibre 5,5 metres long, with a pump power of 23,1 W and a seed power of less than 20 mW, can achieve more than 5,5 W of output power, an ER of more than 10 dB, for a 1543 nm wavelength with a rising/falling time of around 250 ps.

Comparing the obtained values with the simulated ones, it was observed a 20 % deviation, which can be explained mainly due to the insertion loss of several components that where not considered, such as the FC/APC connector (between the insulator and the pump combiner), the pump combiner itself and the splice between the pump combiner and the active fibre.

Although it was only recorded few sets of measures for all the parameters intended to analyse, these results represent a great starting point to improve the transmission channel of the Optical Head. Note that the main goal of this study was to reach 6 W and 10 dB ER.

The results end up being good indicators of the general behaviour rather than absolute values, i.e., it was not that important to reach exactly 6 W, but rather knowing that that value is perfectly achievable. An important information that should be noted is that for the optical head in normal operation mode only 3 W of output power is needed.

Regarding uncertainties on the results, it was not done any analysis, since the achieved values were obtained for the worst-case scenario, where the used components were the available at Lusospace (unless the active fibre) and not selected in a way to optimize the gain. That would mean that if more suitable components were available, better results should be obtained.

Resuming, the tested OFA can be used for the objective this project has, delivering good results, however, if the purpose is to study the system beyond 6 W of output power, it would have to be done a more profound study, possibly having to assemble a different montage/components and active fibre length.

Following the developed work and trying to improve it, one of the options for future work would be the use of a preamplifier (possibly an EDFA or a SOA) to amplify the signal before the developed OFA. However, as explained before, it would be mandatory to verify that the full amplifier is operating out of the saturation regime.

Another option is using a longer fibre that would also provide higher output power results.

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A

STUDY OF GENERIC FIBRES

This appendix contains data obtained for the study carried out on generic optical fibres using the simulator. As mentioned in Section 5.1, this study was carried out iteratively, with the software OptiSystem, taking output power values for different input power values and different pump power values, initially for different fibre lengths (Table A.1) and then for different numerical aperture values (Table A.2). It should be noted that the most satisfactory values for fibre length (marked in green) were defined for the numerical aperture study.

It must be admitted that this study is somewhat limiting, once real fibres are not simulated, but it is an important study to get a better idea of how the parameters behave as a function of each other.

The results marked in green are the ones that respect the values of output power and ER to be obtained. Only having an output power greater than 6 W and an ER around 12 dB, the results are considered as satisfactory.

It is also important to mention that this table does not contain results with its respective uncertainty, as these results were obtained by OptiSystem's mathematical algorithms.

Optical Fibre	Seed Wavelength (nm)	Input Power (mW)	Pump Wavelength (nm)	Pump Power (W)	Fibre Length (m)	Numerical Aperture	Output Power (W)	Backscattered Output Power (W)	Extinction Ratio (dB)
Erbium Doped	1550	1	980	0,1	5	0,24	0,056968	0,002271	4,450
		2					0,058648	0,001677	
		10					0,067824	0,874702	
		100					0,158726	0,465447	
		1		1			0,587319	0,060982	0,897
		2					0,598751	0,044890	
		10					0,621933	0,022414	
		100					0,722022	0,008771	
		1		5			2,772	0,594525	0,628
		2					2,875	0,441531	
		10					3,023	0,221941	
		100					3,203	0,083566	
		1		10			5,307	1,573	0,726
		2					5,567	1,174	
		10					5,947	0,595101	
		100					6,272	0,223615	
		1		15			7,700	2,771	0,832
		2					8,150	2,078	
		10					8,817	1,059	
		100					9,325	0,398275	
Erbium Doped	1550	1	980	0,1	2	0,24	0,031103	0,047411	6,926
		2					0,038082	0,038316	
		10					0,056550	0,022617	
		100					0,153268	0,012831	
		1		1			0,110580	0,820602	7,233
		2					0,168842	0,730374	
		10					0,331325	0,486952	
		100					0,584792	0,229379	
		1		5			0,155134	4,749	11,140
		2					0,280871	4,552	
		10					0,850687	3,664	
		100					2,017	1,962	
		1		10			0,164201	9,735	13,075
		2					0,310262	9,506	
		10					1,115	8,244	
		100					3,333	4,882	
		1		15			0,167502	14,730	14,168
		2					0,321856	14,487	
		10					1,256	13,020	
		100					4,373	8,237	
Erbium Doped	1550	1	980	0,1	3	0,24	0,048185	0,018823	5,152
		2					0,052276	0,014406	
		10					0,065000	0,007856	
		100					0,157816	0,004248	
		1		1			0,348171	0,442043	2,896
		2					0,407660	0,350200	
		10					0,516293	0,192835	
		100					0,678330	0,079867	
		1		5			0,975434	3,447	4,566
		2					1,317	2,909	
		10					2,055	1,755	
		100					2,791	0,737947	
		1		10			1,331	7,881	5,916
		2					1,954	6,901	
		10					3,522	4,433	
		100					5,197	1,932	
		1		15			1,531	12,559	6,865
		2					2,367	11,246	
		10					4,715	7,547	
		100					7,439	3,387	
Erbium Doped	1550	1	980	0,1	2,5	0,24	0,041161	0,030652	5,794
		2					0,046673	0,023943	
		10					0,061896	0,013447	
		100					0,156262	0,007397	
		1		1			0,224885	0,638645	4,562
		2					0,294025	0,531322	
		10					0,439538	0,314521	
		100					0,642970	0,136563	
		1		5			0,445235	4,287	7,462
		2					0,705212	3,879	
		10					1,482	2,665	
		100					2,482	1,227	
		1		10			0,519880	9,169	9,298
		2					0,890851	8,583	
		10					2,272	6,415	
		100					4,423	3,153	
		1		15			0,552275	14,118	10,454
		2					0,983266	13,437	
		10					2,814	10,557	
		100					6,132	5,450	

Table A.1 — Study of the output power and the ER in respect to the length of the fibre

Optical Fibre	Seed Wavelength (nm)	Input Power (mW)	Pump Wavelength (nm)	Pump Power (W)	Fibre Length (m)	Numerical Aperture	Output Power (W)	Backscattered Output Power (W)	Extinction Ratio (dB)
Erbium Doped	1550	1	980	0,1	2,5	0,24	0,041161	0,030652	5,794
		2					0,046673	0,023943	
		10					0,061896	0,013447	
		100					0,156262	0,007397	
		1		1			0,224885	0,638645	4,562
		2					0,294025	0,531322	
		10					0,439538	0,314521	
		100					0,642970	0,136563	
		1		5			0,445235	4,287	7,462
		2					0,705212	3,879	
		10					1,482	2,665	
		100					2,482	1,227	
		1		10			0,519880	9,169	9,298
		2					0,890851	8,583	
		10					2,272	6,415	
		100					4,423	3,153	
		1		15			0,552275	14,118	10,454
		2					0,983266	13,437	
		10					2,814	10,557	
		100					6,132	5,450	
Erbium Doped	1550	1	980	0,1	2,5	0,2	0,035906	0,038658	6,366
		2					0,042602	0,030085	
		10					0,059942	0,016370	
		100					0,155504	0,008564	
		1		1			0,147775	0,760181	6,254
		2					0,215973	0,654495	
		10					0,385702	0,399530	
		100					0,623802	0,166722	
		1		5			0,224247	4,638	10,064
		2					0,395155	4,369	
		10					1,089	3,286	
		100					2,276	1,550	
		1		10			0,241463	9,611	12,064
		2					0,448529	9,285	
		10					1,493	7,645	
		100					3,884	4,008	
		1		15			0,247944	14,601	13,221
		2					0,470495	14,251	
		10					1,722	12,282	
		100					5,205	6,918	
Erbium Doped	1550	1	980	0,1	2,5	0,3	0,044538	0,025538	5,465
		2					0,049245	0,020089	
		10					0,063140	0,011596	
		100					0,156771	0,006613	
		1		1			0,287514	0,539582	3,576
		2					0,350456	0,441935	
		10					0,473857	0,260857	
		100					0,655084	0,117531	
		1		5			0,708489	3,871	5,663
		2					1,015	3,388	
		10					1,766	2,214	
		100					2,610	1,025	
		1		10			0,908461	8,552	7,199
		2					1,418	7,750	
		10					2,905	5,413	
		100					4,767	2,613	
		1		15			1,011	13,390	8,233
		2					1,656	12,372	
		10					3,781	9,028	
		100					6,730	4,504	
Erbium Doped	1550	1	980	0,1	2,5	0,275	0,043489	0,027123	5,564
		2					0,048448	0,021280	
		10					0,062752	0,012171	
		100					0,156608	0,006860	
		1		1			0,267074	0,571895	3,872
		2					0,332514	0,470310	
		10					0,463273	0,277463	
		100					0,651320	0,123438	
		1		5			0,613267	4,022	6,223
		2					0,908939	3,557	
		10					1,675	2,357	
		100					2,570	1,087	
		1		10			0,760759	8,787	7,872
		2					1,227	8,051	
		10					2,699	5,740	
		100					4,661	2,780	
		1		15			0,831961	13,674	8,958
		2					1,405	12,767	
		10					3,459	9,539	
		100					6,545	4,797	

Table A.2 — Study of the output power and the ER in respect to the numerical aperture

Optical Fibre	Seed Wavelength (nm)	Input Power (mW)	Pump Wavelength (nm)	Pump Power (W)	Fibre Length (m)	Numerical Aperture	Output Power (W)	Backscattered Output Power (W)	Extinction Ratio (dB)
Erbium Doped	1550	1	980	0,1	2,5	0,275	0,043489	0,027123	5,564
		2					0,048448	0,021280	
		10					0,062752	0,012171	
		100					0,156608	0,006860	
		1		1			0,267074	0,571895	3,872
		2					0,332514	0,470310	
		10					0,463273	0,277463	
		100					0,651320	0,123438	
		1		5			0,613267	4,022	6,223
		2					0,908939	3,557	
		10					1,675	2,357	
		100					2,570	1,087	
		1		10			0,760759	8,787	7,872
		2					1,227	8,051	
		10					2,699	5,740	
		100					4,661	2,780	
		1		15			0,831961	13,674	8,958
		2					1,405	12,767	
		10					3,459	9,539	
		100					6,545	4,797	
Erbium Doped	1532	1	980	0,1	2,5	0,275	0,047059	0,022654	5,176
		2					0,050275	0,019439	
		10					0,062173	0,013830	
		100					0,154982	0,009864	
		1		1			0,394433	0,378769	2,152
		2					0,429055	0,326621	
		10					0,499763	0,229216	
		100					0,647337	0,139454	
		1		5			1,515	2,624	2,454
		2					1,730	2,290	
		10					2,159	1,634	
		100					2,666	0,983576	
		1		10			2,573	5,970	2,908
		2					3,034	5,250	
		10					3,398	3,792	
		100					5,026	2,294	
		1		15			3,442	9,611	3,256
		2					4,154	8,500	
		10					5,638	6,191	
		100					7,284	3,766	

Table A.3 — Study of the output power and the ER in respect to the seed signal wavelength

B

STUDY OF FIBRES FROM SUPPLIERS

Table B.1 represents results obtained from the study of a total of 15 optical fibres from some suppliers (among them are Thorlabs, iXblue, Coherent and POFC).

As mentioned in Section 5, these simulations are testing real fibres, passible to be acquired in the market. So, the main target to study is the length of the fibre, that is the only parameter of the system that could interfere with the output power. Once parameters such as numerical aperture, doping concentration and core radius cannot be changed from real fibres, and values of seed power or pump power are inherent to the whole system, only the fibre length can be varied.

Therefore, in Table B.1, there is a comparison between these 15 optical fibres, in respect to the values of the output power and the ER. The fibres that result in values similar to the required ones are highlighted in green.

Once again, it is important to mention that this table does not contain the results with its respective uncertainty, as these results were obtained by OptiSystem's mathematical algorithms.

Optical Fibre	Link	Seed Wavelength (nm)	Input Power (mW)	Pump Wavelength (nm)	Pump Power (W)	Fibre Length (m)	Core Radius (µm)	Numerical Aperture	Output Power (W)	Backscattered Output Power (W)	Extinction Ratio (dB)
SM-ESF-7/125	https://content.coherent.com/pdf/pm_esf_7_125_spec_202011122120.pd	1550	1	980	15	4	3,5	0,15	0,324950	14,474	12,425
			100						5,679	6,164	
			1			4,25			0,455036	14,267	11,329
			100						6,180	5,369	
			1			4,5			0,630269	13,989	10,224
			100						6,636	4,646	
			1			5			1,155	13,152	8,073
			100						7,411	3,427	
Er30-4/125	https://www.thorlabs.com/thorproduct.cfm?partnumbe	1550	1	980	15	2,5	2	0,2	0,229841	14,63	13,511
			100						5,159	6,991	
			1			3			0,629800	13,994	10,246
			100						6,665	4,608	
			1			3,5			1,520	12,575	7,079
			100						7,757	2,885	
EDFL-980-HP	https://coherentinc.my.site.com/Coherent/specialty-optical-fibers/ED	1550	1	980	15	2,5	1,4	0,25	0,293505	14,529	12,704
			100						5,470	6,498	
			1			2,75			0,497584	14,204	10,992
			100						6,252	5,258	
			1			3			0,819047	13,693	9,273
			100						6,928	4,192	
			1			3,5			1,934	11,921	6,137
			100						7,947	2,580	
EDFL-1480-HP	https://coherentinc.my.site.com/Coherent/specialty-	1550	1	980	15	3,5	2,25	0,25	0,342937	14,451	11,981
			100						5,412	6,59	
			1			2,5			0,616575	14,016	10,048
			100						6,234	5,288	
			1			5			1,056	13,317	8,174
			100						6,936	4,181	
PM-ESF-7/125	https://coherentinc.my.site.com/Coherent/specialty-optical-fibers/PM-	1550	1	980	15	4	3,7	0,15	0,268649	14,563	12,985
			100						5,342	6,697	
			1			4,25			0,37352	14,397	11,945
			100						5,845	5,899	
			1			4,5			0,514769	14,172	10,884
			100						6,310	5,162	
			1			5			0,942345	13,491	8,780
			100						7,116	3,892	
EDFC-980-HP-80	https://coherentinc.my.site.com/Coherent/specialty-	1550	1	980	15	2,5	1,6	0,23	0,309886	14,503	12,536
			100						5,556	6,362	
			1			2,75			0,526759	14,158	10,801
			100						6,335	5,127	
			1			3			0,867941	13,615	9,069
			100						7,005	4,071	
EDFH0690	https://www.pofc.com/productsView/79	1550	1	980	10	2,5	1,6	0,21	0,161879	9,737	13,501
			100						3,625	4,418	
			1			5			4,043	3,567	1,837
			100						6,171	0,38695	
			1		15	5			5,484	6,275	2,210
			100						9,123	0,713633	
EDFH0790	https://www.pofc.com/productsView/79	1550	1	980	15	3	1,85	0,2	0,526433	14,158	10,921
			100						6,508	4,852	
			1			3,25			0,836041	13,666	9,309
			100						7,131	3,872	
			1			3,5			1,282	12,955	7,757
			100						7,648	3,056	
			1		10	4			2,162	6,561	4,262
			100						5,768	1,021	
EDFH0790	https://www.pofc.com/productsView/79	1550	1	980	15	2,5	1,4	0,25	0,293528	14,529	12,703
			100						5,470	6,498	
			1			2,75			0,497595	14,204	10,991
			100						6,252	5,258	
			1			3			0,819062	13,693	9,273
			100						6,928	4,192	
			1			3,5			1,934	11,921	6,137
			100						7,947	2,580	
SCF-ER-6/125-14	https://www.coractive.com/specialty-optical-fibers/do	1550	1	980	15	4	3	0,14	0,290108	14,529	12,988
			100						5,773	6,015	
			1			4,5			0,561904	14,097	10,810
			100						6,771	4,435	
			1			5			1,039	13,337	8,621
			100						7,564	3,185	
ER8-6 / ER12-6	https://www.coractive.com/specialty-optical-fibers/do	1550	1	980	15	2,5	2	0,22	0,38997	14,376	11,722
			100						5,798	5,978	
			1			2,75			0,667922	13,934	9,917
			100						6,553	4,783	
			1			3			1,097	13,25	8,166
			100						7,192	3,777	
ER35-7	https://www.coractive.com/specialty-optical-fibers/do	1550	1	980	15	2,5	2,75	0,22	0,265913	14,572	12,836
			100						5,109	7,069	
			1			2,75			0,447102	14,284	11,183
			100						5,871	5,863	
			1			3			0,731043	13,833	9,518
			100						6,543	4,797	
EDF-L 1500	https://www.coractive.com/specialty-optical-fibers/do	1550	1	980	15	2,5	3,15	0,25	0,391373	14,373	11,528
			100						5,564	6,348	
			1			3			0,636527	13,983	9,912
			100						6,237	5,282	
			1			3,25			0,999567	13,406	8,344
			100						6,827	4,353	
SMF-28 Ultra 200 Optical Fiber	https://www.corning.com/media/worldwide/coc/docu	1550	1	980	15	5	4,1	0,14	0,438004	14,292	11,422
			100						6,077	5,530	
			1			5,25			0,577586	14,070	10,492
			100						6,468	4,911	
			1			5,5			0,754380	13,788	9,567
			100						6,828	4,344	
Er16-8/125	https://www.thorlabs.com/drawings/5f338c1e50e514b4-	1550	1	980	15	5	4	0,13	0,331071	14,462	12,412
			100						5,769	6,019	
			1			5,5			0,565655	14,088	10,639
			100						6,553	4,775	
			1			6			0,935024	13,500	8,875
			100						7,216	3,731	

Table B.1 — Study of the output power and the ER obtained using optical fibres from some suppliers

C

SYSTEM WITH AN YB-DOPED FIBRE

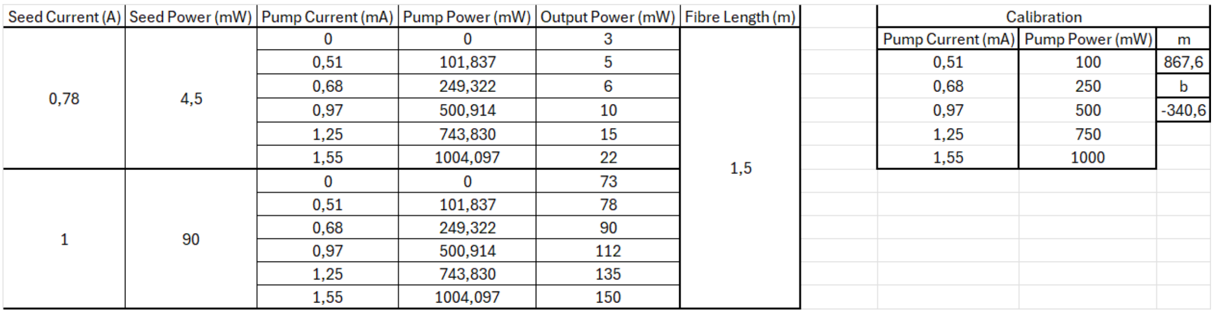
Tables that appear in this Appendix register results obtained with the system described in 6.1. In this montage, as said before, it is used a seed laser of 1064 nm and an Yb-doped optical fibre.

The recording of these values is done, mainly, in order to understand the behaviour of the output power in respect to the pump power. Although the system is different to the one that was decided to use, the fibre is different to the one that is going to be used and the values that are being studied are below the ones that are required, this assembly helps to understand how the system behaves.

It was important to compute a calibration curve because the laser diode controller does not show the pump power of the laser but instead shows the current held by the laser. As such, it was needed to measure both the pump power (before doing the splice, to measure the signal that entered the active fibre) and the current of the laser. With this, it was computed an interpolation to have a relation between the current of the pump and its respective value of pump power.

The registration of the output power values was done through Thorlabs' software of Optical Power Monitor, which does not present uncertainty values of its measures, reason why it does not appear a reference to that in the table.

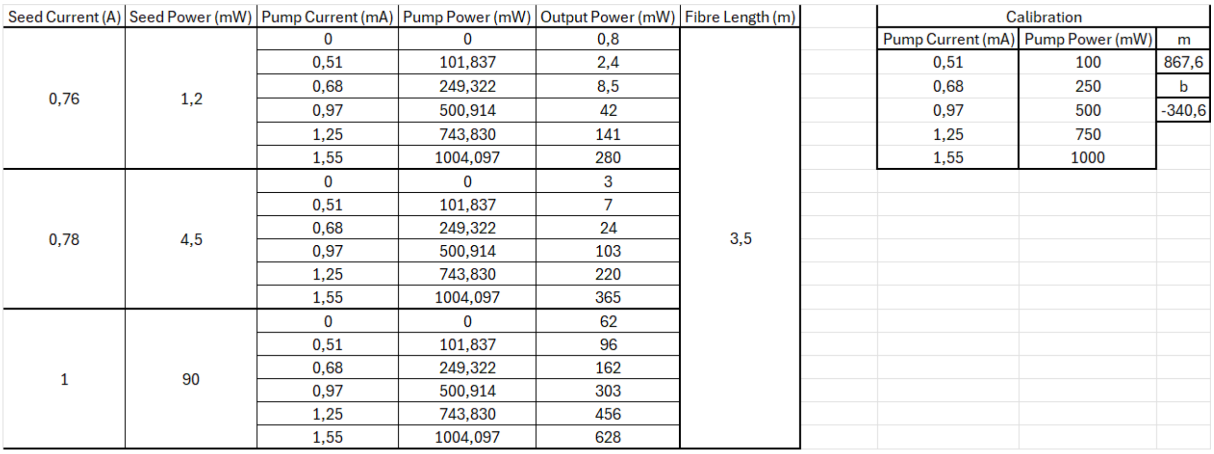
With this study, it was able to see that the fibre length is indeed a factor very relevant to the output power value, and it is important to adapt it according to the value of the output so that it can reach the targeted values. For instance, comparing the values of output power for the seed power of 90 mW and the pump power of 1004 mW, one can see that the fibre of 3,5 meters length has a greater value than the one 1,5 meters long.



Seed Current (A)	Seed Power (mW)	Pump Current (mA)	Pump Power (mW)	Output Power (mW)	Fibre Length (m)
0,78	4,5	0	0	3	1,5
		0,51	101,837	5	
		0,68	249,322	6	
		0,97	500,914	10	
		1,25	743,830	15	
		1,55	1004,097	22	
1	90	0	0	73	
		0,51	101,837	78	
		0,68	249,322	90	
		0,97	500,914	112	
		1,25	743,830	135	
		1,55	1004,097	150	

Calibration		
Pump Current (mA)	Pump Power (mW)	m
0,51	100	867,6
0,68	250	b
0,97	500	-340,6
1,25	750	
1,55	1000	

Table C.1 — Results of the output power for an 1,5-meters Yb-doped fibre



Seed Current (A)	Seed Power (mW)	Pump Current (mA)	Pump Power (mW)	Output Power (mW)	Fibre Length (m)
0,76	1,2	0	0	0,8	3,5
		0,51	101,837	2,4	
		0,68	249,322	8,5	
		0,97	500,914	42	
		1,25	743,830	141	
		1,55	1004,097	280	
0,78	4,5	0	0	3	
		0,51	101,837	7	
		0,68	249,322	24	
		0,97	500,914	103	
		1,25	743,830	220	
		1,55	1004,097	365	
1	90	0	0	62	
		0,51	101,837	96	
		0,68	249,322	162	
		0,97	500,914	303	
		1,25	743,830	456	
		1,55	1004,097	628	

Calibration		
Pump Current (mA)	Pump Power (mW)	m
0,51	100	867,6
0,68	250	b
0,97	500	-340,6
1,25	750	
1,55	1000	

Table C.2 — Results of the output power for an 3,5-meters Yb-doped fibre

D

EQUIPMENT USED IN THE FINAL ASSEMBLY

In Table D.1, it is listed the equipment that was used either for the measurement or for the functioning of the system.

Equipment	Brand and Model	Purpose	Specification
Active Fibre	iXblue IXF-2CF-EY-O-10-130-010-HPA-LL	Amplify the signal	Double Clad Erbium-Ytterbium Fibre; 5,5 metres long; 10 µm core diameter; 125 µm cladding diameter; 0.10 core NA
Amplifier	iXblue DR-DG-12-MO	Amplify the signal from the pulse generator	12.5 GHz
Fibre coupler	Gooch and Housego FFC-CA31A113	Split the signal into multiple outputs used to measure the backscattering	-
Fusion Splicer	Fujikura ARCMaster FSM-100P+	Fuses two fibres to one another	PM fibers
High pass filter	Thorlabs FELH1050	Filter the wavelength the power meter detects	> 1050 nm

High pass filter	Thorlabs FELH1400	Filter the wavelength the power meter detects	> 1400 nm
Low pass filter	Thorlabs FESH1000	Filter the wavelength the power meter detects	< 1000 nm
Modulator	iXblue MXER-LN-10	Transform the signal from the seed laser into a sinusoidal one	10 GHz bandwidth
NIR Absorptive ND Filter	Thorlabs NENIR210B	Attenuate a beam of light	-
Optical Spectral Analyser	Thorlabs OSA 202C	Obtain the optical spectrum of a signal	600 - 1700 nm 7,5 GHz resolution
Oscilloscope	Tektronix MSO 70604C	Represent the output signal	6 GHz; 25 GS/s
Oscilloscope	Rohde & Schwarz RTE 1024	Represent the output signal. This is the one used	200 MHz; 5 GS/s
Pattern Generator	Sympuls PAT3000	This equipment is used to generate a sequence of random messages	Several types of messages can be generated with 1 Gbps
Photodiode	Thorlabs DET08CFC/M	Converts the optical signal into an electrical one. This is the one used	800 - 1700 nm 5 GHz (max) 2 V (max output)
Photodiode	New Focus 1554-B	Converts the optical signal into an electrical one	950–1650 nm 12 GHz (max)
Polarizer	AFW Technologies POBS-15-3	Polarize the light	-
Power Meter	Thorlabs S145C	Detect the power of the signal	800-1700 nm

Power Supply	Agilent E3640A	Supply voltage to the modulator	0 to 8 V/3 A or 0 to 20 V/1.5 A
Power Supply	BK Precision 1665	Supply voltage to the modulator. This is the one used	1-19,99 VDC
Power Supply	Rohde & Schwarz HMP2030	Supply voltage to the amplifier	0 V to 32 V
Pump Combiner	ITF PMC02112A71	Combine the seed signal with the pump signal	50+50 W pump power
Pump Laser	Laser Enterprise BMU15A-980	Provide the pump signal	980 nm 25 W
Pump Laser and respective Cooling System Controller	Hameg HMP4030	Control the current (and consequently the power) of the pump laser and the fan that cools it	-
RF Signal Generator	Tektronix TSG 4106A	Induce a signal in the modulator. Used only for preliminary tests	-
Seed Laser	Gooch and Housego CA1419_194200	Provide the seed signal	1550 nm 100 mW
Seed Laser Controller	Thorlabs ITC4005	Control the current (and consequently the power) and temperature of the seed laser	-
TEC Controller	Thorlabs TED200C	Control the temperature of the pump laser	-

Table D.1 — Equipment and respective functions used for the final assembly

E

FINAL RESULTS OF THE OFA

This appendix contains all the data obtained for the study of the characteristics mentioned in Section 8, well scrutinised along with graphics and tables that help understand them more deeply.

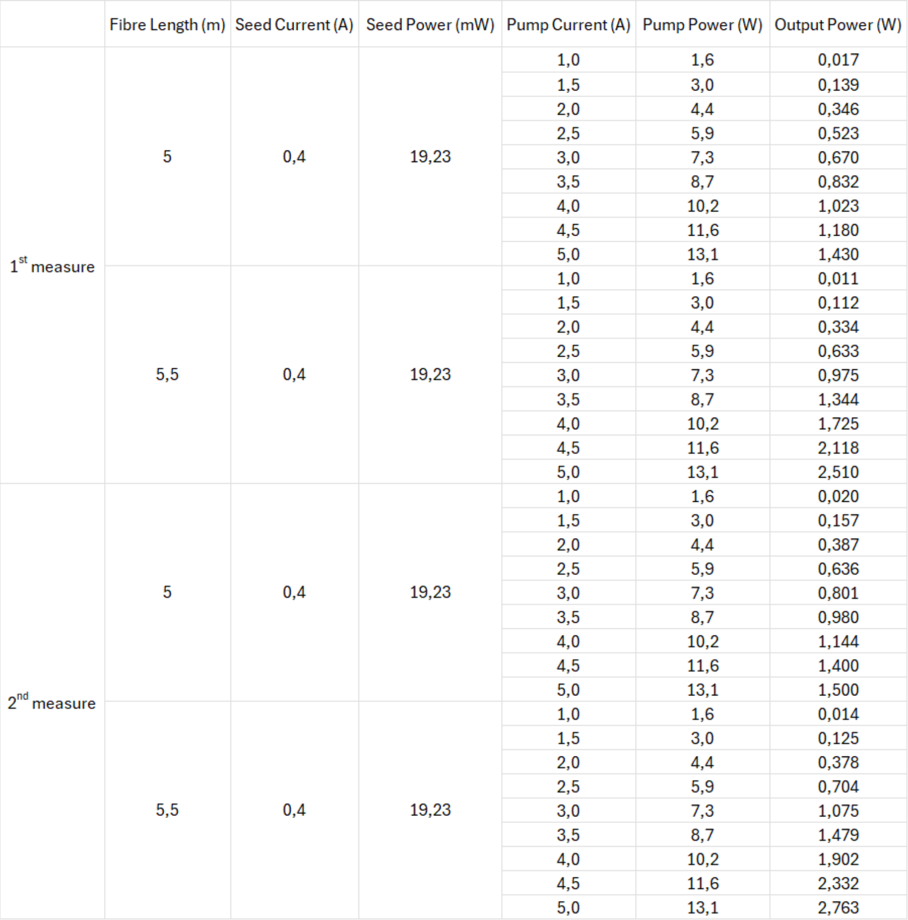
All these results have been taken in just one set of measurements (or two in the case of output power and ER) because the general behaviour of each parameter is more important than the exact value it takes. Furthermore, when taking the values through Thorlabs' programmes or through the oscilloscope, the variation of these results is made so quickly that the value recorded always takes into account the range of values that can be obtained.

E.1 Output Power

Table E.1 represents the results obtained for the test of output power for both a 5,5-metres fibre and a 5-metres fibre. These results were taken in two sets of measures because it was made a small change in the assembly between the two sets, however this change did not affect significantly the results, as it can be seen in Table E.2.

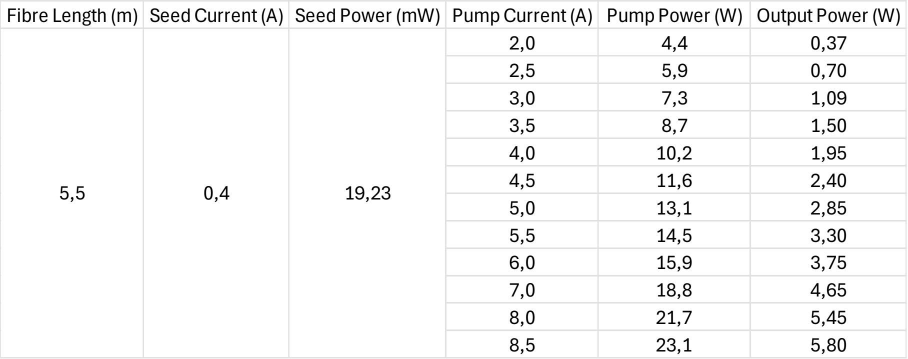
These results made it possible to compute the graphics from Figures 8.1 and 8.2, from Section 8.1.

Since the longest fibre produced the most satisfactory values, it was with the 5,5-metre fibre that the study was carried out for higher pump power values. Table E.2 shows the values from this study. Values for a pump current of 6,5 A, 7,5 A and 9 A or higher were not recorded (although it would be possible to do so) as a matter of precaution. The aim was to get the output power closer to 6 W, which was possible with a pump power of 23,1 W. However, in order to obtain the output power results with a pump power greater than 15 W, the measurements had to be taken very quickly so that the system would not overheat.



	Fibre Length (m)	Seed Current (A)	Seed Power (mW)	Pump Current (A)	Pump Power (W)	Output Power (W)
1st measure	5	0,4	19,23	1,0	1,6	0,017
				1,5	3,0	0,139
				2,0	4,4	0,346
				2,5	5,9	0,523
				3,0	7,3	0,670
				3,5	8,7	0,832
				4,0	10,2	1,023
				4,5	11,6	1,180
				5,0	13,1	1,430
	5,5	0,4	19,23	1,0	1,6	0,011
				1,5	3,0	0,112
				2,0	4,4	0,334
				2,5	5,9	0,633
				3,0	7,3	0,975
				3,5	8,7	1,344
				4,0	10,2	1,725
				4,5	11,6	2,118
				5,0	13,1	2,510
2nd measure	5	0,4	19,23	1,0	1,6	0,020
				1,5	3,0	0,157
				2,0	4,4	0,387
				2,5	5,9	0,636
				3,0	7,3	0,801
				3,5	8,7	0,980
				4,0	10,2	1,144
				4,5	11,6	1,400
				5,0	13,1	1,500
	5,5	0,4	19,23	1,0	1,6	0,014
				1,5	3,0	0,125
				2,0	4,4	0,378
				2,5	5,9	0,704
				3,0	7,3	1,075
				3,5	8,7	1,479
				4,0	10,2	1,902
				4,5	11,6	2,332
				5,0	13,1	2,763

Table E.1 — Results of the output power for a 5-metres fibre and a 5,5-metres fibre



Fibre Length (m)	Seed Current (A)	Seed Power (mW)	Pump Current (A)	Pump Power (W)	Output Power (W)
5,5	0,4	19,23	2,0	4,4	0,37
			2,5	5,9	0,70
			3,0	7,3	1,09
			3,5	8,7	1,50
			4,0	10,2	1,95
			4,5	11,6	2,40
			5,0	13,1	2,85
			5,5	14,5	3,30
			6,0	15,9	3,75
			7,0	18,8	4,65
			8,0	21,7	5,45
			8,5	23,1	5,80

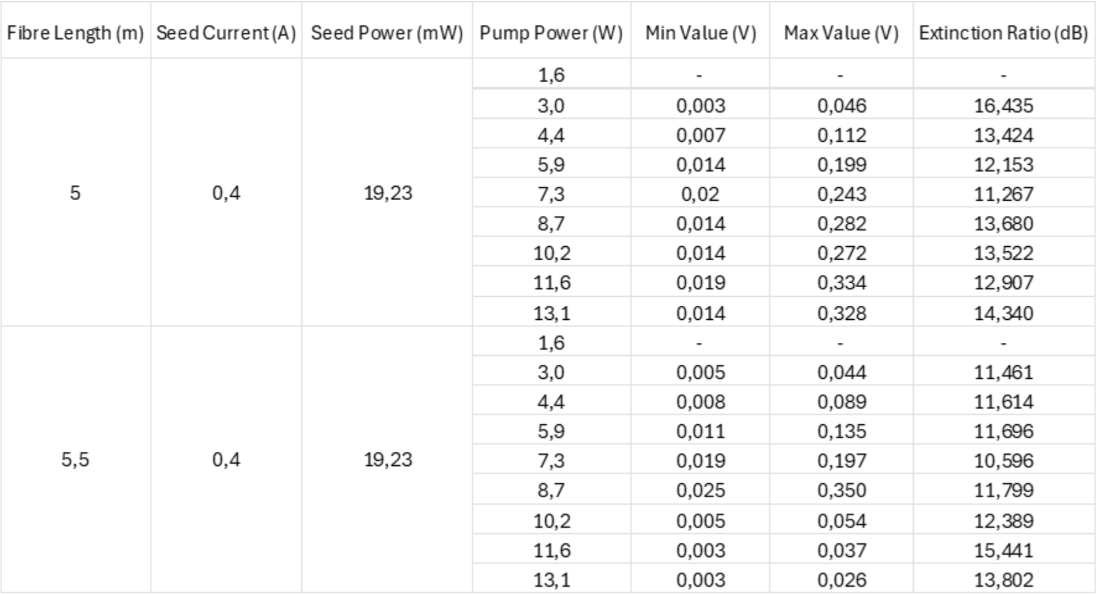
Table E.2 — Final results of the output power for a 5,5-metres fibre

E.2 Extinction Ratio

To calculate the ER, the minimum and maximum value of the sine wave that the output signal represented on the oscilloscope was recorded, from which 2 mV was taken, which was the offset value for the switched off signal.

However, for a pump power higher than 10 W, which represented an output power higher than 1,7 W, it was necessary to make use of a near-infrared absorptive neutral density filter between the face end of the active fibre and the fibre connected to the photodetector. This is why, for a pump current higher than 4 A, the minimum and maximum value of the signal are lower than for the 3,5 A of pump current.

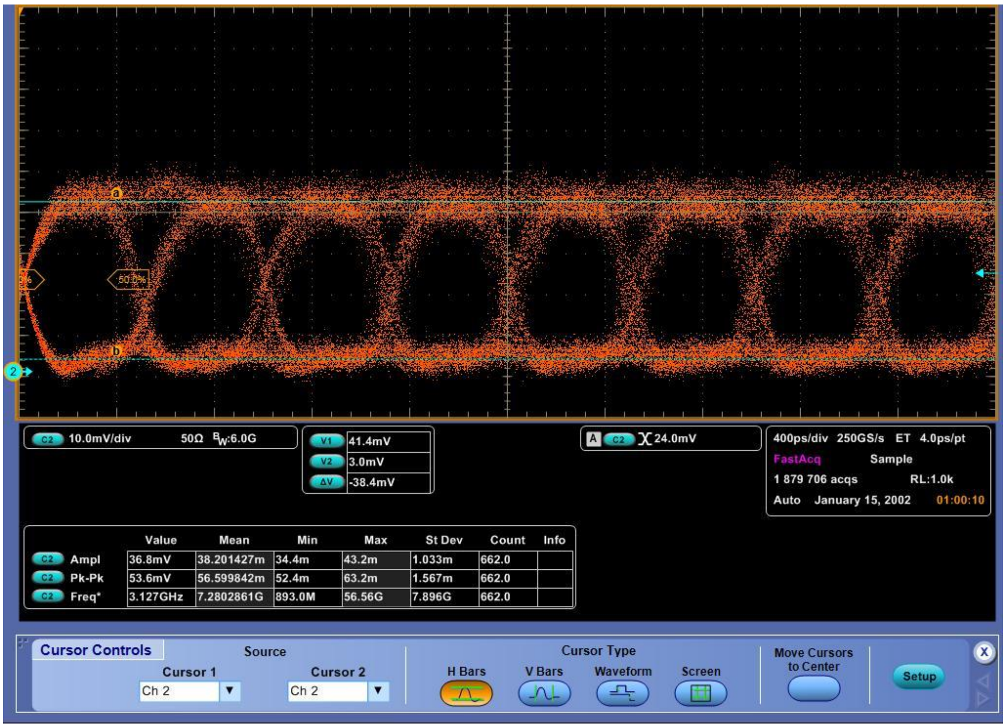
It was not recorded values of ER for a pump power of 1,6 W, since it was not possible to see a perfect sinusoid in the oscilloscope.



Fibre Length (m)	Seed Current (A)	Seed Power (mW)	Pump Power (W)	Min Value (V)	Max Value (V)	Extinction Ratio (dB)
5	0,4	19,23	1,6	-	-	-
			3,0	0,003	0,046	16,435
			4,4	0,007	0,112	13,424
			5,9	0,014	0,199	12,153
			7,3	0,02	0,243	11,267
			8,7	0,014	0,282	13,680
			10,2	0,014	0,272	13,522
			11,6	0,019	0,334	12,907
			13,1	0,014	0,328	14,340
5,5	0,4	19,23	1,6	-	-	-
			3,0	0,005	0,044	11,461
			4,4	0,008	0,089	11,614
			5,9	0,011	0,135	11,696
			7,3	0,019	0,197	10,596
			8,7	0,025	0,350	11,799
			10,2	0,005	0,054	12,389
			11,6	0,003	0,037	15,441
			13,1	0,003	0,026	13,802

Table E.3 — Extinction Ratio values for the two different length fibres

From the observation of Figure E.1, figure captured for the calculation of the time between on/off connection, it is possible to see, that even for a frequency of 2 Gb/s, the ER is above 10 dB. The minimum value of the signal is 3 mV, the maximum value of the signal is 41,4 mV, so the ER is 11,4 dB.



C2 10.0mV/div 50Ω BW:6.0G

V1 41.4mV
V2 3.0mV
ΔV -38.4mV

A C2 ╳ 24.0mV

400ps/div 250GS/s ET 4.0ps/pt
FastAcq Sample
1 879 706 acqs RL:1.0k
Auto January 15, 2002 01:00:10

	Value	Mean	Min	Max	St Dev	Count	Info
C2 Ampl	36.8mV	38.201427m	34.4m	43.2m	1.033m	662.0	
C2 Pk-Pk	53.6mV	56.599842m	52.4m	63.2m	1.567m	662.0	
C2 Freq*	3.127GHz	7.2802861G	893.0M	56.56G	7.896G	662.0	

Cursor Controls
Source
Cursor 1: Ch 2
Cursor 2: Ch 2

Figure E.1 — Eye-diagram of the output signal at a frequency of 2 Gb/s used for the calculation of ER

E.3 Operating wavelength bandwidth

Figure E.2 represents the wavelength of the output power signal, while Figures E.3 and E.4 represent the wavelength bandwidth of the seed signal:

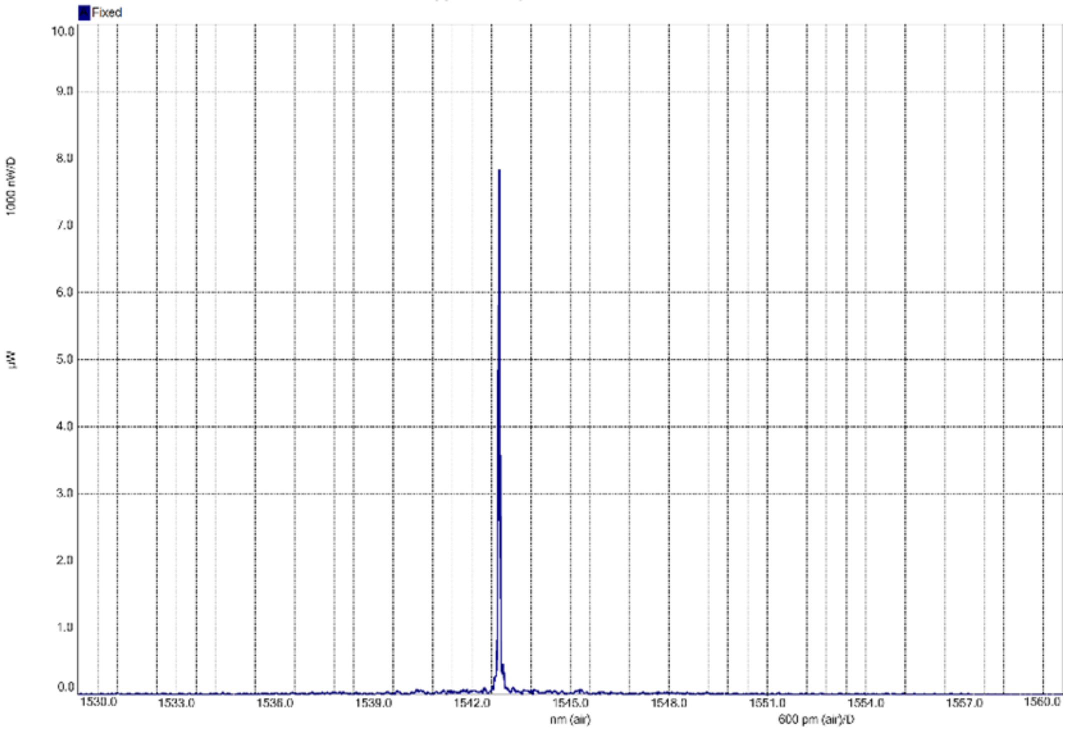


Figure E.2 — Distribution in wavelength of the signal of the output power for a pump of 7,3 W

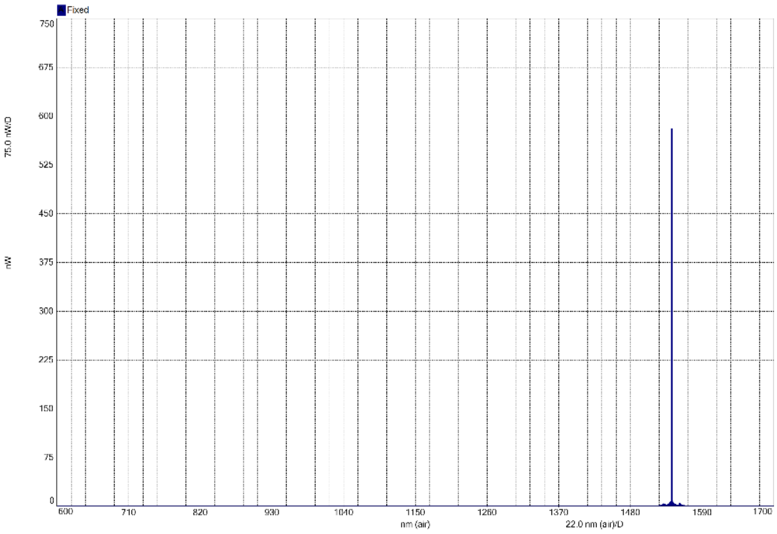


Figure E.3 — Distribution in wavelength of the seed signal

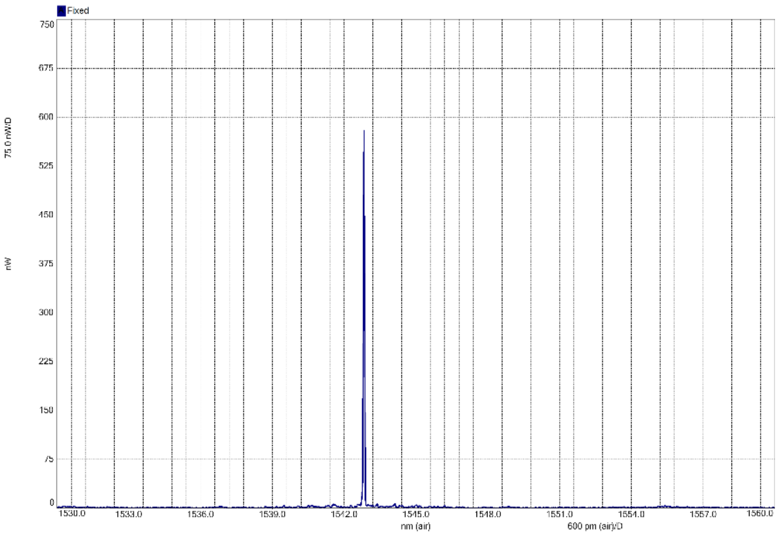


Figure E.4 —Distribution in wavelength of the seed signal (zoomed in)

Comparing this spectrum with the one of Figure 8.6, one can conclude that the wavelength of both is the same, approximately 1550 nm. This is a result that not only was expected but also proves the amplification does not affect the operating wavelength.

Another aspect that was possible to observe was the wavelength of the output power that was backpropagated. Its spectrum is recorded in Figure E.5 and E.6:

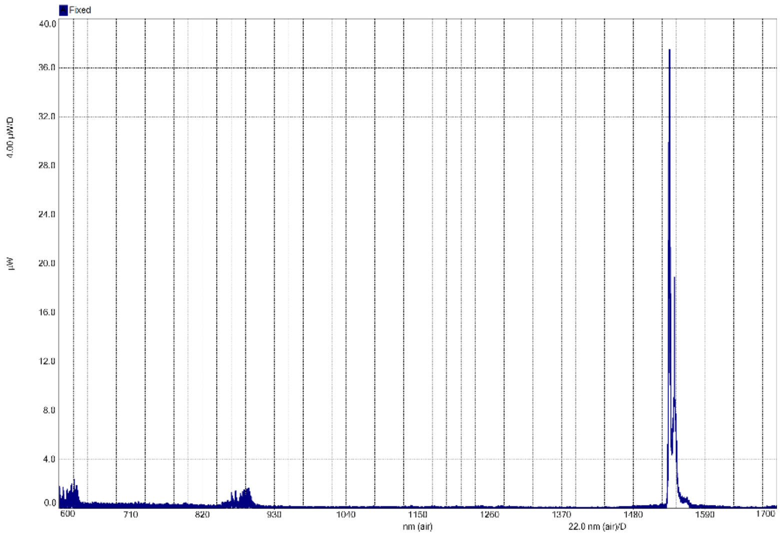


Figure E.5 —Distribution in wavelength of the backpropagated output signal

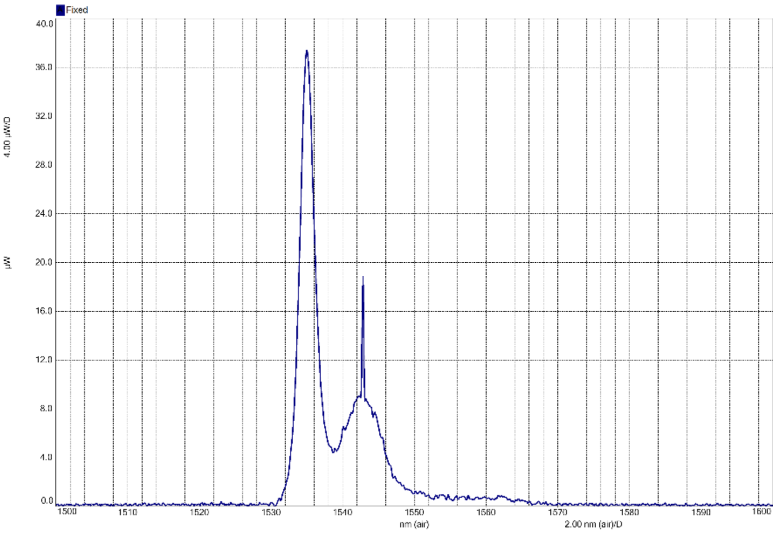
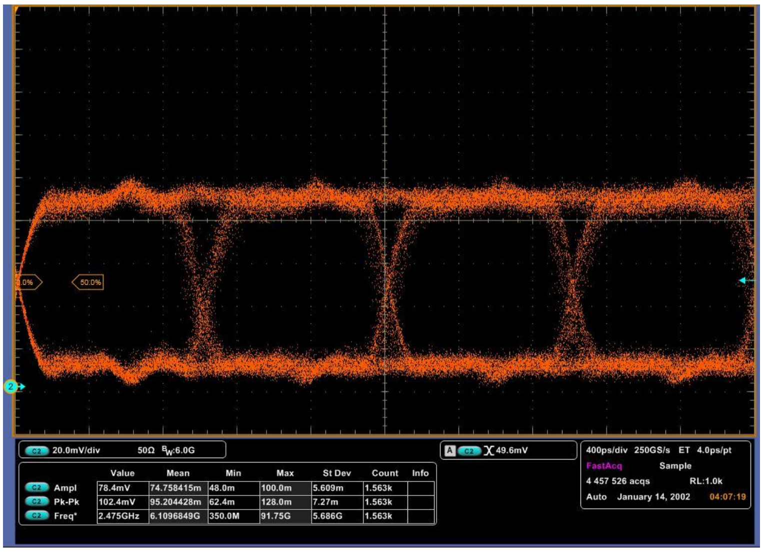


Figure E.6 —Distribution in wavelength of the backpropagated output signal (zoomed in)

From the analysis of these spectra, it can be noticed that, instead of seeing a perfect vertical line around the 1550 nm, it is represented a range of wavelengths, making the original line into a lump. This happens because of the internal reflection and interference between the light that is travelling in the forward direction and the one travelling in the backward direction.

E.4 Time between the on/off connection

For the time between the on/off connection, as explained in Section 8.4, it was generated some eye diagrams, represented in Figures 8.7, E.1 and E.7.



C2 20.0mV/div 50Ω B_W:6.0G

A C2 X 49.6mV

400ps/div 250GS/s ET 4.0ps/pt
FastAcq Sample
4 457 526 acqs RL:1.0k
Auto January 14, 2002 04:07:19

	Value	Mean	Min	Max	St Dev	Count	Info
C2 Ampl	78.4mV	74.758415m	48.0m	100.0m	5.609m	1.563k	
C2 Pk-Pk	102.4mV	95.204428m	62.4m	128.0m	7.27m	1.563k	
C2 Freq*	2.475GHz	6.1096849G	350.0M	91.75G	5.686G	1.563k	

Figure E.7 —Eye-diagram of the output signal at a frequency of 1 Gb/s

From looking at all these figures, it can be concluded that the time is the same for all of them. This means that the time between the on/off connection depends neither on the power of the pump nor on the frequency, but rather on the modulation itself.

E.5 Residual Pump Power

Table E.4 represents the results from the Residual Pump Power, in respect to the pump power and to the output power, from which it was able to compute the graphics from Figure 8.8.

	Fibre Length (m)	Seed Current (A)	Seed Power (mW)	Pump Current (A)	Pump Power (W)	Output Power (W)	Residual Pump Power (W)
1st measure	5,5	0,4	19,23	1,0	1,6	0,011	0,024
				1,5	3,0	0,112	0,058
				2,0	4,4	0,334	0,101
				2,5	5,9	0,633	0,146
				3,0	7,3	0,975	0,194
				3,5	8,7	1,344	0,235
				4,0	10,2	1,725	0,280
				4,5	11,6	2,118	0,320
				5,0	13,1	2,510	0,355

Table E.4 —Results from the Residual Pump Power for a 5,5-metres fibre

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