



UNIVERSITAT
POLITÈCNICA
DE VALÈNCIA

— **TELECOM** ESCUELA
TÉCNICA **VLC** SUPERIOR
DE INGENIERÍA DE
TELECOMUNICACIÓN

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

School of Telecommunications Engineering

Design and implementation of a picosecond laser for the
manufacture of optical devices

End of Degree Project

Bachelor's degree in Engineering Physics

AUTHOR: Fernández Sastre, Gabriel

Tutor: Sales Maicas, Salvador

Cotutor: Barrera Vilar, David

ACADEMIC YEAR: 2024/2025



UNIVERSITAT
POLITÈCNICA
DE VALÈNCIA

— **TELECOM** ESCUELA
TÉCNICA **VLC** SUPERIOR
DE INGENIERÍA DE
TELECOMUNICACIÓN



Resumen

Se aborda el diseño, implementación y caracterización de un sistema láser pulsado de estado sólido y su aplicación en la fabricación de sensores de fibra óptica. El proyecto se desarrolló en tres fases principales. La primera consistió en la caracterización del láser fundamental a 1047 nm, obteniéndose pulsos ultracortos de 9 ps con una potencia de pico de 13,33 MW a una frecuencia de 2 kHz. El siguiente paso fue la implementación de un sistema de generación de segundo armónico (SHG) mediante un cristal LBO. Se logró una notable eficiencia de conversión del 49% para generar un haz estable a 523,5 nm. Finalmente, sobre la base de los resultados obtenidos en las fases anteriores, el haz generado se empleó para la inscripción de una red de difracción de período largo (LPG) en una fibra óptica monomodo. Se fabricó con éxito una LPG funcional con una atenuación de resonancia de aproximadamente 9 dB en la longitud de onda teórica de 1530 nm, mediante una configuración de enfoque con un objetivo de alta magnificación (50x). Los resultados validan la viabilidad del sistema desarrollado como una plataforma versátil para la microfabricación en fibra óptica.

Resum

S'aborda el disseny, la implementació i la caracterització d'un sistema làser polsat d'estat sòlid i la seua aplicació en la fabricació de sensors de fibra òptica. El projecte es va desenvolupar en tres fases principals. La primera va consistir en la caracterització del làser fonamental a 1047 nm, obtenint-se polsos ultracurts de 9 ps amb una potència de pic de 13,33 MW a una freqüència de 2 kHz. El pas següent va ser la implementació d'un sistema de generació de segon harmònic (SHG) mitjançant un cristall LBO. Es va aconseguir una notable eficiència de conversió del 49% per a generar un feix estable a 523,5 nm. Finalment, sobre la base dels resultats obtinguts en les fases anteriors, el feix generat es va emprar per a la inscripció d'una xarxa de difracció de període llarg (LPG) en una fibra òptica monomode. Es va fabricar amb èxit una LPG funcional amb una atenuació de ressonància d'aproximadament 9 dB en la longitud d'ona teòrica de 1530 nm, mitjançant una configuració d'enfocament amb un objectiu d'alta magnificació (50x). Els resultats validen la viabilitat del sistema desenvolupat com una plataforma versàtil per a la microfabricació en fibra òptica.

Abstract

The design, implementation, and characterization of a solid-state pulsed laser system and its application in the fabrication of fibre optic sensors are addressed. The project was developed in three main phases. The first consisted of characterizing the fundamental laser at 1047 nm, achieving ultrashort pulses of 9 ps with a peak power of 13.33 MW at a 2 kHz repetition rate. The next step was the implementation of a second-harmonic generation (SHG) system using an LBO crystal. A remarkable conversion efficiency of 49% was achieved to generate a stable beam at 523.5 nm. Finally, based on the results from the previous phases, the generated beam was employed for the inscription of a long-period grating (LPG) in a single-mode optical fiber. A functional LPG was successfully fabricated with a resonance attenuation of approximately 9 dB at the theoretical wavelength of 1530 nm, using a focusing setup with a high-magnification (50x) objective. The results validate the viability of the developed system as a versatile platform for fiber optic microfabrication.

EXECUTIVE SUMMARY

The Bachelor's thesis of the Degree in Engineering Physics must develop in the text the following concepts, appropriately justified and discussed, focusing on the field of engineering physics.

CONCEPT (ABET)	CONCEPTO (traducción)	¿Cumple? (S/N)	¿Dónde? (páginas)
1. IDENTIFY:	1. IDENTIFICAR:		
1.1. Problem statement and opportunity	1.1. Planteamiento del problema y oportunidad	S	1, 50-51
1.2. Constraints (standards, codes, needs, requirements & specifications)	1.2. Toma en consideración de los condicionantes (normas técnicas y regulación, necesidades, requisitos y especificaciones)	S	13, 30, 35-39
1.3. Setting of goals	1.3. Establecimiento de objetivos	S	4, 5
2. FORMULATE:	2. FORMULAR:		
2.1. Creative solution generation (analysis)	2.1. Generación de soluciones creativas (análisis)	S	16-20, 36-40, 43-46
2.2. Evaluation of multiple solutions and decision-making (synthesis)	2.2. Evaluación de múltiples soluciones y toma de decisiones (síntesis)	S	10, 13, 40, 45, 46
3. SOLVE:	3. RESOLVER:		
3.1. Fulfilment of goals	3.1. Evaluación del cumplimiento de objetivos	S	41, 48, 50
3.2. Overall impact and significance (contributions and practical recommendations)	3.2. Evaluación del impacto global y alcance (contribuciones y recomendaciones prácticas)	S	50-52



Acknowledgements

I would like to express my sincere gratitude to all the people who, in one way or another, have contributed to the completion of this Final Bachelor Thesis.

First, I am deeply grateful to my supervisors, David Barrera and Salvador Sales, for their guidance, patience, and invaluable advice. Their guidance has been essential in shaping this project and ensuring its rigor. I am especially grateful for their help in developing my lateral thinking through various alignment methods.

On a personal level, this work is dedicated to my family. To my parents, Angela Sastre Santos and Fernando Fernández Sastre, for their unconditional support, love, and constant encouragement. To my brother, Fernando Fernández Sastre, thank you for your continuous motivation.



Table of contents

Chapter 1.	Introduction	1
1.1	Problem Context: Why is this Laser Relevant?	1
1.2	State of the Art: Contemporary Developments in Pulsed Laser Technologies and Fiber Optic Sensing	2
1.3	Objective of the Work	4
1.3.1	Specific Objectives	4
Chapter 2.	Theoretical Background	6
2.1	Laser Operation	6
2.2	Picosecond Characteristics	7
2.3	Second Harmonic Generation	10
2.4	Second Harmonic Generation Crystals	13
2.5	Parameters to consider	13
2.6	Theoretical foundations of LPGs	14
Chapter 3.	Design and Characterization of a Picosecond Laser System	16
3.1	Laser Working Principle	16
3.1.1	Pumping Configuration	16
3.1.2	Gain Medium and Thermal Mounting	16
3.1.3	Laser Cavity	18
3.1.4	Acousto-Optic Q-Switch	19
3.1.5	Pin Holder	20
3.1.6	Laser Display and Alignment	20
3.2	Technical Specifications	22
3.2.1	Average Power	22
3.2.2	Pulse Parameters	23
3.2.3	Polarization and Wavelength	29
3.3	Laser Modulation	30
3.4	Beam Profile	31
3.4.1	BeamMaster Software	31
3.4.2	Quantitative Analysis	33



3.5	Safety Regulations.....	35
Chapter 4.	Implementation of a Multiwavelength Laser	36
4.1	Crystal Election	36
4.1.1	Geometrical Properties	36
4.1.2	Physical-Optical Properties	37
4.2	SHG Configuration.....	39
4.3	Characterization of SHG	40
4.3.1	Conversion Efficiency	41
4.3.2	Generated Wavelength	41
4.3.3	Beam Profile	41
4.3.4	Angular dependency	42
Chapter 5.	LPG Inscription and Sensing Capabilities.....	43
5.1	Configuration.....	43
5.1.1	Fibre Adjustment	43
5.1.2	Beam alignment and compression.....	44
5.1.3	Reconfiguration of the system.....	45
5.2	Inscription Process.....	47
5.3	Results	48
5.3.1	Spectral Analysis	48
5.3.2	Potential in optical sensing.....	49
Chapter 6.	Conclusions and Future Projects	50
	Bibliography.....	53

Table of figures

Figure 1. Stimulated absorption, spontaneous emission, and stimulated emission processes. Adapted from [17].	6
Figure 2. Illustration of the Q-switching process, showing the build-up of energy in the gain medium (blue line) and the subsequent release of a short, intense laser pulse when the Q-switch is opened (dashed red line).	8
Figure 3. Relationship between the temporal and spectral domains for laser pulses. The bottom row offers an enlarged view for clarity.	8
Figure 4. Operating principle of an acousto-optic modulator. Adapted from [18]	9
Figure 5. Absorption coefficient of Yb:YAG crystal for different pumping wavelengths. Source: [22]	16
Figure 6. The Stokes shift corresponding to an absorption at 940 nm and an emission at 1047 nm.	17
Figure 7. Stability diagram for a semi-confocal laser cavity. It shows the stability parameter and the normalized beam radius as a function of cavity length.	18
Figure 8. Photograph of the picosecond laser experimental setup, showing the key optical components.	21
Figure 9. Spectral responsivity curve of the Thorlabs DET08CFC photodetector. Source: [26]	24
Figure 10. Oscilloscope trace showing the laser pulse train. The time base is 250 μ s/div.	25
Figure 11. Optical spectrum of the laser output measured with the OSA and markers positioned 5dB below peak value.	26
Figure 12. Optical spectrum of the laser output measured with the OSA and markers positioned at the widest part of the beam.	27
Figure 13. Oscilloscope trace of a single laser pulse.	27
Figure 14. Operation of a linear polarizing filter, which only allows the electric field component parallel to its transmission axis to pass. Adapted from [9].	29
Figure 15. Simulation of the effect of repetition rate on laser performance.	31
Figure 16. Evolution of the elliptical beam profile at different propagation distances (20 cm, 50 cm, and 100 cm).	34
Figure 17. Spectrum of the second harmonic generation (SHG) output. The peak is centered at 523.5 nm.	41

Figure 18. Normalized power of the second harmonic generated as a function of the crystal rotation angle.	42
Figure 19. Laser system for fibre inscription.	45
Figure 20. Incidence of the collimated beam on the coated optical fibre.....	45
Figure 21. Laser system with magnification lens for fibre inscription.....	46
Figure 22. Incidence of the collimated beam on the fibre nucleus.....	47
Figure 23. Diagram of the LPG inscription process.....	48
Figure 24. Spectral response of a LPG inscribed in single-mode fibre using a picosecond laser system with a grating period of 365 μm and a total length of 7 cm. ..	48



List of Tables

Table 1. Comparison of different Q-switching methods	10
Table 2. Comparison of different nonlinear crystals.	13
Table 3. Summary of the characterized parameters of the fundamental laser beam.	30
Table 4. Beam profile parameters measured at a distance of 20 cm using BeamMaster software.	32
Table 5. Beam profile parameters measured at a distance of 100 cm using BeamMaster software.	32
Table 6. Calculated refractive index for the LBO crystal at the fundamental and second harmonic wavelengths.	38
Table 7. Characterization of the second harmonic beam diameter at a distance of 20 cm.	42



Abbreviations and Acronyms

BBO	β -BaB ₂ O ₄ , a nonlinear crystal (Table 2, pag. 13)
BLDC	brushless direct current motor
CW	continuous-wave
FBG	fibre Bragg gratings
FWHM	full width at half maximum
GVD	group velocity dispersion
HR	highly reflective
IC	integrated circuit
KTP	KTiOPO ₄ , a nonlinear crystal (Table 2, p. 13)
LBO	LiB ₃ O ₅ , a nonlinear crystal (Table 2, p. 13)
LED	light-emitting diode
LIDT	laser-induced damage threshold
LPG	long-period grating
NCPM	noncritical phase matching
NIR	near infrared
OSA	spectral optic analyser
PI	<i>Physik Instrumente</i>
PPLN	LiNbO ₃ , a nonlinear crystal (Table 2, p. 13)
PRL	Photonics Research Labs
QPM	quasi phase-matching
RF	radiofrequency
SA	saturable absorbers
SDG	sustainable development goals
SHG	second-harmonic generation
TBP	time-bandwidth product
UV	ultraviolet
Yb:YAG	ytterbium doped in an yttrium aluminium garnet, a gain medium

Chapter 1. Introduction

1.1 Problem Context: Why is this Laser Relevant?

Pulsed lasers, defined as short pulses of high-energy beams, offer many possibilities for interesting applications. Their high-energy pulses enable very precise material interactions with unique thermal attributes that stand out from other conventional techniques. Their uses range from sensing applications (which will be the subject of this study) other basic-science, technological and industrial applications in fields such as medicine, physics, chemistry, energy generation, topography, food processing, or water treatment [1], to cite some. It is also important to highlight their integration in the nanomaterials (<100 nm) creation process, using the top-down approximation, which allows bulk production in astounding time frames as well as being a non-toxic (environmentally conscious) very affordable method [2]. They operate in such a wide range of uses due to their compact, low-maintenance, and high-reproducibility characteristics.

Ultrashort-tuned lasers have gained traction in recent years for their applications in precise microfabrication, especially in sensor production, as they have shown an unparalleled ability to inscribe fibre Bragg gratings (FBGs) [3]. FBGs are one of the most widely used devices for implementing optical fibre sensors, due to the inscribed periodic modulation which reflects specific wavelengths of light while transmitting others. Sensing applications are not limited to FBGs, as it has been shown and proven the inscription of LPG (Long Period Grating) to create robust and high stable sensors [4], as well as Mach Zehnder interferometers [5].

Ultrashort-pulse laser inscription in optical fibres occurs through multiphoton absorption, which allows material interaction using visible or near-infrared radiation. The cladding or fibre core does not absorb this radiation, but only at the focal point, ensuring that surrounding regions remain unaffected. This is the reason for the high precision and stability of the structures generated by this method [3]. Under certain configurations, it is possible to inscribe FBGs and LPGs without the need to remove the protective polymer fibre coating. Since the protective coating remains intact, the mechanical integrity of the fibre section containing the inscribed grating is preserved [6].

By exposing optical fibres to focused beams of intensities exceeding 10^{13} W/cm², it induces a nonlinear absorption [7]. The energy deposition over a timeframe of picoseconds results in an electron plasma within the focal volume that transfers its energy to the bulk material. This process leads to permanent structural modifications, including refractive index changes, localized melting, defect formation, nanograting inscription, and even void generation, depending on the laser intensity and irradiation parameters [7].

Optical sensors serve as an indispensable option for various industrial applications. One of their primary differentiations is their electromagnetic immunity, whereas traditional sensors' performance would degrade over time in an electromagnetic prevalent environment, optic sensors prevail and perform accordingly, as expected. In fields such as power generation and aerospace, where data acquisition with conventional sensors proves challenging, optical sensors ensure reliable measurements. In addition to this, optical sensors deliver high sensitivity and accurate readings whilst being flexible and having capabilities for remote and distributed sensing, giving them a wide range of practical uses in structural maintenance and other fields such as biomedical diagnostics [8].

As demonstrated, a solid-state multi-wavelength picosecond laser is an indispensable piece of equipment to have finely tuned, characterized and ready to use for its previously mentioned features. The proposed object of study of the thesis will be a laser developed at ITEAM, specifically within the PRL (Photonics Research Labs) group. One of the main lines of research of this group is fibre optic sensing, as evidenced by the large number of scientific publications (more than 50 Q1s in the last 10 years), the technology transfer agreements that have emerged with companies or entities such as Airbus, ESA, Ford, etc., and the patents, some of which have already been licensed to companies. The laser that is planned to be implemented is intended to manufacture sensing devices that will be applied in these lines of work, and therefore, the development of this project is very important for the line of work being developed at ITEAM.

The development of the laser outlined in this proposal will enable the fabrication of novel sensors, which can be applied to ongoing funded research projects as well as to future national, European, and regional research proposals. Additionally, it will contribute to potential technology transfer activities.

1.2 State of the Art: Contemporary Developments in Pulsed Laser Technologies and Fiber Optic Sensing

A great variety of pulsed lasers are capable of modulating optical fibres for sensing applications, each with its own characteristics that make them suitable for different and unique situations. Some of the most notable examples include lasers such as the femtosecond laser (10^{-15} s), the picosecond laser (10^{-12} s) or the nanosecond laser (10^{-9} s) [9]. Apart from the pulse duration, they can be defined by the active medium used in the laser cavity. They can be classified as excimer lasers (e.g., KrF at 248 nm, ArF at 193 nm), CO₂ lasers (wavelength around 10.6 μ m), Nd:YAG lasers (wavelengths at 1064 nm, 532 nm, 266 nm), and fibre lasers (various wavelengths depending on the doping material) [10].

The defining characteristics of pulsed lasers, being the wavelength, pulse duration, pulse energy, and repetition rate, serve as an indicator of the most competent application for any given laser in the field of sensing. Wavelength directly links to the photon energy and

the method in which the photons interact with the fibre material, which can be either absorption or transparency [9]. Near infrared wavelengths (800 nm - 1550 nm) are employed for non-photosensitive fibre and inscriptions with femtosecond lasers [7], whereas visible wavelengths are most used for direct inscription techniques [11]. Alternatively, UV wavelengths are employed in processes needing inscriptions on photosensitive and polymer fibres [3], and CO₂ lasers working in the mid-infrared range (10.6 μ m) are primarily suited for microfiber tapering and LPG inscription [12].

Other parameters like pulse duration define the timeframe of interaction between the fibre material and the laser, defining if the ablation is thermal or non-thermal. For ultrashort pulses like in the femtosecond and picosecond range, there is a nonlinear absorption that leads to a very precise inscription and a near non-existent heat absorption of the surrounding material [13]. The pulse's energy will determine the extension of the refractive index change produced by the laser, and can be intuitively understood as more power will translate to a bigger change. The power will be adjusted depending on the need and characteristics of the final sensor, as an excess of power can prove detrimental for certain applications [14].

Finally, regarding the repetition frequency, a high repetition rate can lead to a rapid succession of pulses interacting with the fibre, enhancing the refractive index change, but can lead to thermal instability and damage within the fibre. On the other hand, low repetition rates will help maintain the structural integrity of the fibre as it will lead to better heat dissipation, but in exchange, require longer processing times [15]. Depending on the fibre material, the type, the desired characteristics of the sensor, the required manufacturing accuracy, and the speed, a specific type of pulsed laser will be selected.

The different types of pulsed lasers and different inscription techniques give rise to distinct sensors. One of the most common and versatile would be the long-period grating (LPG) [16]. There are various inscription techniques defined by different laser parameters that produce LPGs with unique characteristics. Ultra-short pulsed lasers fabricate LPGs through the modulation of the refractive index of the fibre core, with periods from 100 μ m up to 1 mm [12]. The point-by-point method is commonly used in these configurations.

The point-by-point inscription technique induces a localized refractive index change in a point of the fibre's core via nonlinear absorption, and then a very precise translation stage moves the focal point to the next point, in order to create the periodic pattern of the LPG. It is a flexible method that serves in special fibres' inscriptions (fibres with unique structural, material, or functional properties that differ from regular fibres and are used for specific or tailored applications), and for personalized sensors, allowing the preservation of the mechanical resistance of the fibre by, in some cases, being able to inscribe through the cladding.

By modulating periodically, the refractive index along the length of the fibre, at certain resonant wavelengths light stops propagating through the nucleus, coupling to cladding modes that suffer from heavy losses [17]. Light coupled to cladding modes fades rapidly, hence the transmission spectrum is heavily attenuated for said wavelengths.

Resonant wavelengths are sensitive to variations in temperature, strain or refractive index changes in the fibre environment, which justifies its widespread application in sensing technologies [8]. In particular configurations, with various resonant wavelengths, a singular LPG can detect and distinguish between changes in temperature and tension. Other prevalent applications include, but are not limited to, measuring the refractive index of the environment, taking advantage of the fact that the cladding modes are more sensitive to changes in the external environment [17].

Fabrication of LPGs is not limited to pulsed lasers, nonetheless, utilizing this method offers several advantages. Traditional methods include UV lasers, electric arc, chemical etching, and mechanical microbending [12]. Ultra-short lasers stand out from the rest due to their precision and ability to create complex structures [7]. This structural complexity is manifested in the possibility of designing chirped gratings or integrating localized defects within the fibre. Moreover, they offer unparalleled versatility, being able to inscribe in different types of optical fibre, including non-photosensitive ones.

The potential impact of pulsed lasers in distinct industries and applications is undeniably significant. Most notably, the deployment of advanced fibre-optic sensors manufactured with pulsed lasers will enable new sensing paradigms and applications previously limited by traditional sensor technologies. Electrical sensors, although functional, are not as reliable as optical sensors that provide high sensitivity and are compatible with hostile environments. This field is dynamic and continuously evolving, with investigation now centring around the development of more efficient and cost-effective manufacturing techniques as well as new diverse applications.

1.3 Objective of the Work

This bachelor's thesis aims to design, implement, and characterize a picosecond pulsed laser system with second harmonic generation, and to employ it for the inscription of a LPG in an optical fibre, evaluating its viability for sensing applications.

1.3.1 Specific Objectives

- To study the theoretical foundations of laser pulse generation using Q-Switch modulation and its suitability for nonlinear optical processes.
- To design and optimize a picosecond laser system centred at 1047 nm.
- Implement an experimental setup that allows for efficient second harmonic generation, using a nonlinear LBO crystal.
- Experimentally characterize the properties of the fundamental beam and the second harmonic beam, including parameters such as wavelength, optical power, and spatial profile.



- Create an optical configuration for efficient fibre inscription based on beam compression techniques.
- Using the second harmonic beam to inscribe an LPG in an optical fibre by localized irradiation.
- Evaluate the quality of the generated LPG through its spectral response, analysing its potential applicability in optical sensing systems.
- Comment on the experimental results and propose possible improvements to the developed system.

Chapter 2. Theoretical Background

2.1 Laser Operation

Laser operation is based on the fundamental process of electron excitation. By supplying external energy, either with optical pumping (light) or electrical discharge, the electrons of the atoms or molecules inside the laser medium will rise to higher energy levels. When the electron returns spontaneously from the excited state to a lower energy one, a photon is liberated. This process is known as spontaneous emission, which is commonly seen in incoherent light sources such as LEDs. In contrast, stimulated emission is the driving process in light generation in Lasers. This happens when an incident photon with the energy of the bandgap between two energy bands interacts with the excited electron. This induces the decay of the electron to the lower energy level and the emission of a photon with identical characteristics to the incident. The emission of photons with indistinguishable energy, phase, and direction leads to a highly directional, coherent, and narrowband light [17]. The differences between the different types of emissions are illustrated in Figure 1.

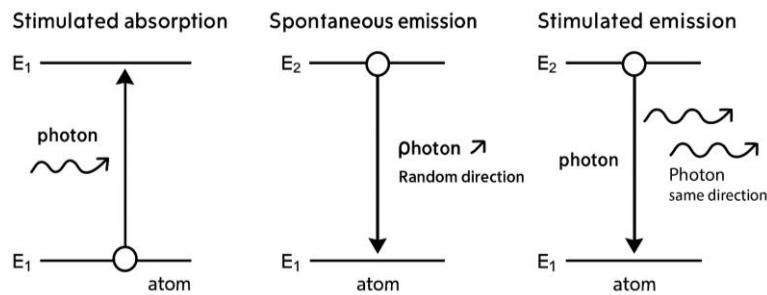


Figure 1. Stimulated absorption, spontaneous emission, and stimulated emission processes. Adapted from [17].

The laser medium enables the stimulated emission that generates the laser light. In the case of solid-state and fibre lasers (most relevant in this case) the gain medium is crystals or fibre, respectively, doped with rare-earth metal ions. For a laser oscillation in the gain medium to occur, a population inversion is required, which is a state where the quantity of excited atoms or molecules far exceeds that of the molecules in the lower energy states. It is essential that the absorption rate be lower than the stimulated emission rate for population inversion, which is achieved via pumping external energy into the cavity to excite atoms [17].

Stimulated emission percentage of working must exceed the losses in the system for there to be a substantial gain in the medium and therefore, lasing conditions [18, 19]. This effect is achieved via the use of optical resonators that provide positive feedback. The resonators enable an amplification of the gain in the active medium by confining light and making it interact with the medium multiple times. The design of these resonators typically consists of two mirrors: one highly reflective and one partially transmissive, enabling the

repeated interaction of light within the medium, which sustains the population inversion required for the operation of the laser [18].

The characteristics of these resonators will greatly influence the laser's efficiency and output characteristics, meaning that ensuring an optimal resonator geometry and mirror traits will lead to a coherent and directional light emission.

2.2 Picosecond Characteristics

Picosecond lasers generate ultrashort pulses of light of the order of picoseconds (10^{-12} s). This, in turn, facilitates the study of ultrafast phenomena in key areas of study in physics, chemistry, and biology, among others.

There are multiple techniques available to achieve ultrashort pulses of light. Active techniques utilize external modulators inside the cavity to periodically modify the amplitude or frequency of light. Modifying the amplitude creates a shutter effect that eliminates long pulses, whereas by modulating the frequency, new frequencies are added to the laser modes. If the frequencies match the spacing of the cavity modes, mode locking occurs. On the contrary, passive techniques utilize elements within the cavity that are sensitive and reactive to light intensity, thus affecting their optical properties. Lenses with the Kerr effect, whose refractive index changes depending on light intensity, are commonly employed and result in mode locking that favours high-intensity pulses [18].

Other techniques can be employed, for example, the one used in the laser that is the object of study, such as Q-switching. This highly efficient method stores energy within the gain medium that is then liberated as a short, directional, and intense pulse of light. Q-switching is a slower method compared to the previous ones but can reach ultra-short pulses with highly aligned and maximized configurations. This process is controlled by the quality factor (Q) [18]. The quality factor is defined as:

$$Q = 2\pi \cdot \frac{\text{Stored Energy}}{\text{Energy Dissipated per Cycle}} \quad (2.1)$$

By altering the intracavity losses of the system, the quality factor can be controlled to be within two distinct phases. In the storage phase, a low Q factor is achieved by the introduction of artificial losses in the laser cavity that will impede laser emission. This, in turn, will lead to an increase in the population inversion over the spontaneous emission threshold, therefore accumulating huge amounts of energy inside the gain medium. The emission phase, as its name indicates, releases in an instant a high-power and short-duration laser pulse when rapidly eliminating the intracavity losses that were introduced. As shown in Figure 2, the emission will happen before the population inversion can be reestablished. It can also be observed how the slope is not infinite as the pulse emission takes a few cavity cycles to complete, meaning the system has a finite physical response.

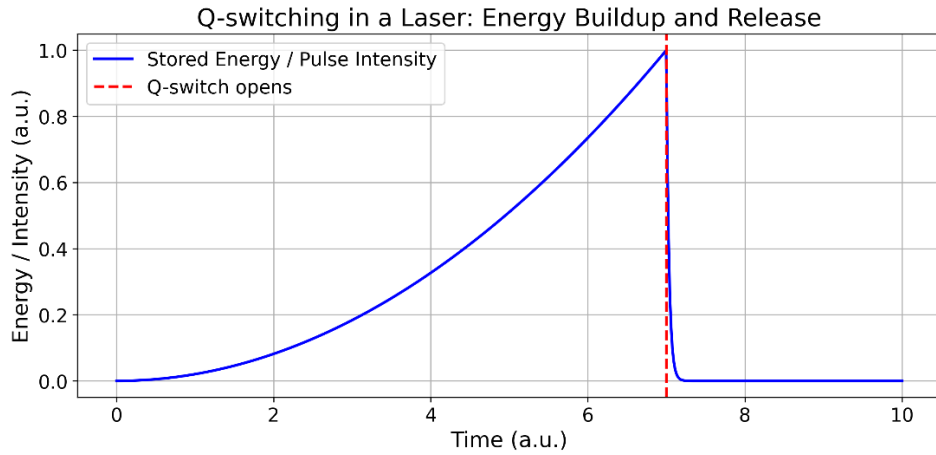


Figure 2. Illustration of the Q-switching process, showing the build-up of energy in the gain medium (blue line) and the subsequent release of a short, intense laser pulse when the Q-switch is opened (dashed red line).

There exists an inverse relationship between the duration of the pulse and the spectral bandwidth; picosecond pulses will exhibit a large spectral bandwidth due to the relationship between the Fourier transform of both temporal and spectral domains. This relationship can be incurred and seen in Figure 3, showing that the shorter the pulse in the time domain, the wider its spectral frequency will be. These parameters are related with the TBP (Time-bandwidth product), an adimensional parameter expressed by the formula [18]:

$$TBP = \Delta\tau \cdot \Delta\nu \quad (2.2)$$

Where $\Delta\tau$ is the pulse duration and $\Delta\nu$ is the spectral bandwidth. TBP is a constant value related to the shape of the pulse, meaning a higher value of TBP indicates a pulse with a non-constant spectral phase, a chirped pulse.

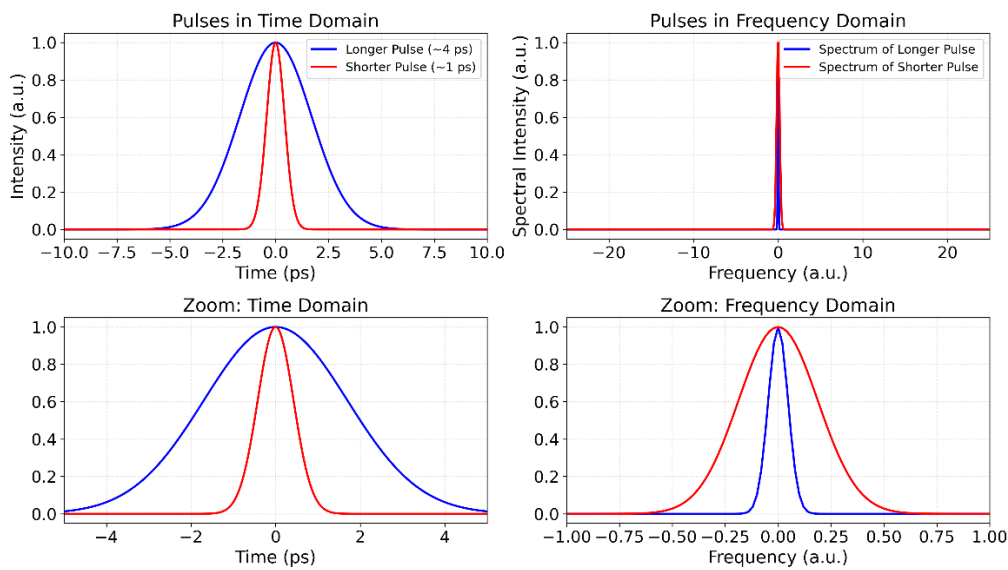


Figure 3. Relationship between the temporal and spectral domains for laser pulses. The bottom row offers an enlarged view for clarity.

To achieve Q-switching, there are active and passive methods with distinct mechanisms and characteristics [18]. Active Q-switching requires an externally controlled device that regulates the intracavity losses and therefore the Q factor. Within this category, common methods include electro-optic, acousto-optic, and mechanical methods.

Electro-optic switching consists of a voltage-controlled modulator that changes the polarization of the light. When there is a voltage, a change in the polarization prevents light propagation, causing heavy losses in the system and accumulating energy. When the voltage is no longer supplied to the modulator, light can go through the polarizer, and the pulse is released.

Acousto-optic modulators work differently as it is Radiofrequency (RF) driven. An acoustic wave will generate a diffraction grating in the crystal (the modulator), making light scatter from the cavity. When the beam interacts with the grating, it divides into various diffraction orders (0, ± 1 , ± 2 , etc.). The diffraction efficiency quantifies the proportion of energy that is deflected from the fundamental order or beam trajectory. A diagram to show the basic functioning is shown in Figure 4. When there is no more RF signal, the pulse is released.

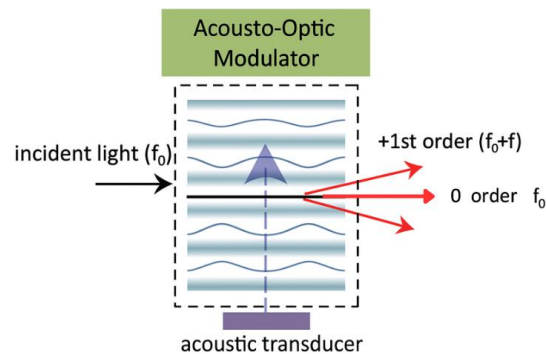


Figure 4. Operating principle of an acousto-optic modulator. Adapted from [18]

Mechanical Q-switching is not very complex when compared to the two previous methods, as it consists of a rotating mirror that allows breaking the positive feedback chain of the optical resonator and restoring it. Passive modulation techniques use primarily saturable absorbers (SA), which absorb photons when illuminated with low intensity light, accumulating energy, but become transparent for high intensity light. In Table 1, the four methods are compared, and it can be seen how mechanical methods have become outdated, and that the others differ in their uses and applications. Electro-optic has a higher energy pulse as it has very low residual loss compared to other methods, as the acousto-optic method will suffer from diffraction losses, and SA can introduce losses due to their intensity-dependent saturation.

	Speed	Pulse Energy	Complexity	Applications
Electro-Optic	High (~ns-ps)	High	High	Precision machining, lidar
Acousto-Optic	High (~ns -ps)	Medium	Medium	Laser marking, spectroscopy
Mechanic	Low (~ms)	Low	Low	Early lasers (rare today)
Saturable Absorber	High (~ns-ps)	Medium-Low	Low	Compact pulsed Lasers, medical

Table 1. Comparison of different Q-switching methods

2.3 Second Harmonic Generation

Lineal optics display a proportional relationship between the polarization of the material and the electric field applied to light. Nevertheless, at high field intensities, light stops responding linearly, which can be represented as the non-linear terms becoming significant. Nonlinear polarization is expressed as a power series of the electric field [20]:

$$(E): P = \epsilon_0(\chi^{(2)}E^2 + \chi^{(3)}E^3 + \dots) \quad (2.3)$$

Where $\chi^{(n)}$ is the susceptibility of the n^{th} order. Second order nonlinearities are processes which present a governing second order susceptibility, $\chi^{(2)}$, second harmonic generation is part of it. Typical materials that exhibit this characteristic are those who exhibit a non-centrosymmetric crystalline structure. This structure main attribute is its lack of an inversion centre, which means that when the structure is inverted, it is not symmetric.

Second harmonic generation can be described through a monochromatic light with frequency ω and an electric field:

$$E(\omega) = E_0 \cos(\omega t) \quad (2.4)$$

Light when propagating through a nonlinear medium with a dominant $\chi^{(2)}$ will display a second order polarization with the value described by inserting (2.4) in (2.3) and taking other susceptibilities as insignificant.

$$P^{(2)}(t) = \epsilon_0 \chi^{(2)} E_0^2 \cos^2(\omega t) \quad (2.5)$$

This equation can be developed with trigonometry to obtain:

$$P^{(2)}(t) = \frac{1}{2} \epsilon_0 \chi^{(2)} E_0^2 + \frac{1}{2} \epsilon_0 \chi^{(2)} E_0^2 \cos(2\omega t) \quad (2.6)$$

The first term of the equation (2.6) represents the generation of direct current field, otherwise referred to as the optic rectification, meanwhile the second term refers to the nonlinear polarization with a 2ω frequency that will irradiate the second harmonic light. In simple terms, second harmonic generation (SHG) is a process in which two photons of the same frequency of the input light, when interacting with the nonlinear medium,

produce a single photon with double the frequency (and consequently half the wavelength) [20]. Energy is conserved, as although the frequency doubles and so does the energy, the interaction of the two photons results in only one output photon. Another particularity of SHG is that as the energy is doubled, the intensity of the second harmonic wave ($I_{2\omega}$) is directly proportional to the intensity of the input wave (I_ω).

The second order susceptibility ($\chi^{(2)}$) is a tensorial quantity and determines the efficiency of the SHG. A bigger susceptibility value translates to a more efficient conversion between the fundamental frequency and the second harmonic frequency. This parameter is highly sensitive to the orientation and polarization of the crystal medium.

To ensure an efficient SHG, the propagation between the fundamental and the generated second harmonic wave must be in phase for there to be constructive interference. This phase relation should be maintained for considerable distances. If there is a phase discrepancy between the waves, the second harmonic light will interfere destructively and lower the conversion efficiency. This condition is called phase-matching [20].

Phase matching is quantified with the wave vector mismatch of both frequencies:

$$\Delta k = k_{2\omega} - k_\omega \quad (2.7)$$

$$\Delta k = \frac{2\omega}{c} (n_{2\omega} - n_\omega) \quad (2.8)$$

In both equations, k represents the magnitude of the wave vector and n the refractive index of the respective frequencies. The perfect and ideal condition for phase matching would be when $\Delta k = 0$, meaning that the refractive index would be identical in both cases ($n_{2\omega} = n_\omega$). Another key parameter that defines the SHG efficiency is the coherence length, that is the distance from which the SHG signal stops being in phase with the input light.

$$L_c = \frac{\pi}{|\Delta k|} = \frac{\lambda}{4|n_{2\omega} - n_\omega|} \quad (2.9)$$

A small value of the coherence length means that the fundamental and second harmonic waves will rapidly fall out of phase, limiting the SHG efficiency. A perfect phase matching would give an infinite L_c , which would be ideal, but in reality, the dispersive nature of materials prevents it. To achieve a potent SHG, phase matching is indispensable, as without it, a small value of the coherence length will limit the conversion efficiency.

To achieve phase matching and a condition of $\Delta k \approx 0$, different types of techniques can be used. These techniques aim to nullify the negative effects the material's dispersion has on SHG. The three most common are birefringence, quasi-phase matching, and noncritical phase matching.

Birefringent crystals have a different refractive index depending on the incident light polarization. When the input light is parallel to the optic axis of the crystal, the material will present a value of n_e , meanwhile polarization orthogonal to said axis will present a refractive index value of n_o . Adjusting the orientation of the crystal and the input

polarization of the light, birefringence can be exploited to achieve a phase-matching condition.

There are two types of birefringence for phase-matching, commonly referred to as Type I and Type II synchronism [20, 21]. Type I synchronism happens when two photons with identical polarization combine to generate a second harmonic photon that has an orthogonal polarization to them. The crystal orientation is carefully aligned for the second harmonic refractive index ($n_{2\omega}^e$) to be equal to the fundamental refractive index of its orthogonal polarization (n_{ω}^o), and vice versa. This method is typically used in ultrashort laser pulses but has its limitations as it is highly dependent on the crystal's orientation.

On the other hand, Type II synchronism happens when two photons of orthogonal polarizations combine to generate a second harmonic photon with one of the original polarizations. The alignment of the crystal requires the following condition to be satisfied:

$$\frac{n_{\omega}^o + n_{\omega}^e}{2} = n_{2\omega}^e \text{ or } n_{2\omega}^o \quad (2.10)$$

The orientation in Type II is less sensitive to temperature and more tolerant towards angle deviation than Type I, although it requires a more efficient and powerful external pumping source.

Quasi-phase matching is used in materials that do not exhibit high enough birefringence properties, so in order to achieve $\Delta k \approx 0$, an artificial modulation is introduced in the material. The crystal is modified to have its domain inverted periodically. A way to achieve this would be by changing the orientation of its dipoles. Whenever light travels a distance Λ (polarization period), the nonlinear coefficient's sign will change, rebooting the phase shift. This will prevent energy conversion from oscillating and will, in turn, continue growing. The compensatory wavevector introduced by this method is:

$$\Delta k_{\text{QPM}} = \Delta k - \frac{2\pi m}{\Lambda} \quad (2.11)$$

Where m is the quasi-phase matching order, which is usually 1 for maximum efficiency. QPM, unlike the birefringence technique, does not have a polarization dependence, and its spectral adjustment is tunable by changing the polarization period [20].

The third method, Noncritical Phase Matching, takes advantage of some crystal's temperature dependence and their specific crystallographic directions to achieve phase matching conditions. Nonlinear crystals, such as KTP, for example, have temperature-varying refractive indices. The temperature can be adjusted until $\mathbf{k}_{2\omega} = 2\mathbf{k}_{\omega}$ condition is reached. To be able to generate SHG with as much efficiency as possible, light must travel through the crystallographic axis of the crystal where birefringence is minimal. This method, in comparison, proves to have a very low beam separation (low walk-off) and very high stability and efficiency, being implemented in high-power continuous wave lasers [20].

2.4 Second Harmonic Generation Crystals

There is a wide variety of nonlinear crystals used for second harmonic generation. The use of each individual crystal will depend on the application, as they all have different properties that make them suitable for distinct configurations. The main characteristics that will define the use of a crystal are the transparency range, the nonlinear coefficient, and its birefringence [21].

The transparency region is crucial, as it is the wavelength range for which the crystal transmits light without significant absorption losses. This means that both the fundamental and the second harmonic wavelengths should be within this range to prevent losses. The nonlinear correlation has a direct correlation with the efficiency of SHG, as the parameter quantifies the nonlinear interaction that the crystal provides. The type and magnitude of birefringence will determine the possible phase-matching technique utilised and its alignment.

Other parameters to consider are the damage threshold and the working wavelength of the laser. The damage threshold is important to consider as high-power lasers can impair the crystal's normal functioning, even permanently damaging it. The wavelength determines previous attributes and will influence the stability of the overall system.

Crystal	Chemical Formula	Transparency Region (nm)	Nonlinear Coefficient (pm/V)	Phase matching	Damage Threshold (GW/cm ²)	Applications
KDP	KH_2PO_4	200-1500	~0.4-1.0	Type I, Type II	~1-5	SHG in Nd:YAG
BBO	$\beta - BaB_2O_4$	190-2600	~1.7-2.7	Type I, Type II	~0.1-0.5	SHG in Ti:safiro, UV generation
LBO	LiB_3O_5	160-2600	~0.7-1.2	Type I, Type II, NCPM	~5-20	SHG and THG in Nd:YAG
KTP	$KTiOPO_4$	350-4500	~2-3.5	Type II, QPM	~0.1-1	SHG in Nd:YAG
PPLN	$LiNbO_3$	400-5000	~27-35	QPM	~0.01-0.1	SHG in near infrared

Table 2. Comparison of different nonlinear crystals.

Table 2 shows the unique properties each crystal displays. It is noticeable the PPLN's nonlinear coefficient, as it has a highly efficient conversion but is very delicate due to its low damage threshold. LBO is also notorious for its durability as it can endure significantly more than other crystals.

2.5 Parameters to consider

When introducing SHG within an ultrashort pulsed laser system, there are some factors to take into account, as they can hinder optimal lasing conditions, and the proper functioning. As the laser's pulses shorten and its peak power rises, advanced nonlinear concepts can arise and assume more relevance. The main effects to consider are group velocity dispersion

(GVD), autofocus, and high-order nonlinearities. In picosecond laser systems, having precise control over them will maximize the efficiency and quality of the light beam.

GVD appears as the velocity of a train of pulses depends on the wavelength [18, 20]. This leads to a temporal broadening of the pulse as the different spectral components of the picosecond pulse will travel at slightly distinct velocities. In the case of a pulsed laser with SHG, GVD can lead to a separation of the fundamental and the second harmonic waves, limiting the interaction and nonlinear efficiency. If the effect is present, GVD can be compensated with dispersive elements such as prisms or gratings.

Autofocus is an optical phenomenon that occurs in high-power lasers. When propagating through a medium, the high power will induce a slight variation in the refractive index of the medium. This will make the beam narrower, mimicking the effect of a lens. The critical Power (P_{cr}) depends on the nonlinear coefficient of the medium and the laser's wavelength. A value that surpasses P_{cr} will likely hinder SHG as the beam can suffer from spatial distortion or the nonlinear crystal can be damaged.

Also, it is worth considering the higher-order nonlinearities that are present in ultrashort and high-powered pulses. Typically, third-order nonlinearities ($\chi^{(3)}$) are prevalent in these situations and can take away part of the fundamental power necessary for SHG [20]. An optimized modelling of the laser system design will prevent nonlinearities of different orders from having a dominant role.

2.6 Theoretical foundations of LPGs

A long-period fibre grating (LPG) is an optical fibre structure that features a periodic variation along its length, specifically designed to couple light from a guided core mode into cladding modes propagating in the same direction. In contrast with other structures (like Fibre Bragg Gratings, FBGs), the wavelength of the propagated radiation is considerably smaller than the period of the FBG [16]. The relative simplicity in their fabrication stems directly from this larger grating period.

The fundamental operating principle of the LPG lies in the coupling of cladding and core modes with matching propagation constants. In a standard single-mode fibre, the fundamental core mode (LP_{01}) can couple to several higher-order cladding modes. A selective spectral loss results from the wavelength dependence of the coupling. When both modes couple, the energy transferred to the cladding modes dissipates rapidly. Absorption and scattering at the cladding interface are the predominant causes of this phenomenon. For the resonant wavelengths, the energy loss manifests as distinct attenuation in the transmission spectrum of the fibre. Multiple resonance wavelengths are possible; the coupling of the fundamental core mode to any cladding mode is represented as different attenuation peaks. This ability to block specific wavelengths while allowing others to pass leads to LPGs effectively functioning as band-rejection filters.

Since the modes are required to be co-propagating to couple, their respective propagation constant (β) must closely match. The phase matching condition is given by [16]:

$$\Delta\beta = \frac{2\pi}{\Lambda} \quad (2.12)$$

Where $\Delta\beta$ is the difference in propagation constants between the coupled modes and Λ is the grating period. From 2.12 it is established that for a close match between propagation constants, a large grating period is required. This large period, which may range from hundreds of micrometres to millimetres, is a direct physical consequence of the mode-coupling mechanism. The variation of the grating's period results in precise control over the attenuation bands. The resonant wavelength depends on the period and the effective refractive index of the core and cladding of the fibre. This relation is displayed by [16]:

$$\lambda_{\text{Res}} = (n_{\text{eff,co}} - n_{\text{eff,cl}}) \cdot \Lambda \quad (2.13)$$

The attenuation peaks caused by the phase-matching condition induced by the gratings is not merely an observed phenomenon. The position, depth, and width of the peaks are highly sensitive to changes in the fibre's surrounding environment. The direct response to refractive index, temperature, or strain changes makes an LPG into a highly effective optical sensor.

Ultra-short pulses are utilized to induce periodic gratings in the fibre. The interaction of ultrashort pulses with transparent materials, such as an optical fibre, leads to local structural modifications and changes in the refractive index. Per photoexcitation of the material and associated nonlinear processes, a laser excitation on picosecond scales and at high repetition rates can achieve a significant increase in the refractive index (densification) [7]. By rapidly depositing substantial amounts of energy in a very small volume, the material locally expands, launching pressure waves through the fibre. Within the irradiated zone, the waves cause mechanical stress, influencing the local refractive index. The modification is not solely a direct laser-induced effect, but also involves subsequent mechanical relaxation. Furthermore, exposing the fibre to a series of laser pulses progressively modifies the structure based on the effects left by the previous ones. This leads to cumulative effects, enhancing the change in density and further altering the refractive index.

The produced densification is not a simple linear process. In order to design an effective grating configuration, a complex interaction of pulse parameters and material properties must be considered. The underlying complexity of LPG inscription in fibres justifies the need for a sophisticated laser system with precise control over the inscription process to achieve the desired periodic modulation of the refractive index.

Chapter 3. Design and Characterization of a Picosecond Laser System

The laser configuration presented here is composed of Ytterbium doped in an Yttrium Aluminium Garnet (Yb:YAG) gain medium emitting at 1047 nm, which is considered near infrared. The objective of this chapter will be the discussion of the design, functioning, and performance of the system as well as its characterization.

3.1 Laser Working Principle

3.1.1 Pumping Configuration

To effectively excite the upper lasing level and reach lasing conditions, the crystal medium is pumped using a 2 V diode laser source that emits at 940 nm. As observed in Figure 5, this wavelength corresponds to one of the primary absorption peaks of Yb:YAG, resulting in an effective electron excitation and population inversion [22]. The power of the diode laser directly correlates with the overall lasing performance, as a higher pump energy will lead to higher output power. Nonetheless, excessive pump power can cause an increase in the thermal load of the crystal and degrade the beam quality. The 2 V serves as a compromise in order to achieve the best possible results for fibre inscription.

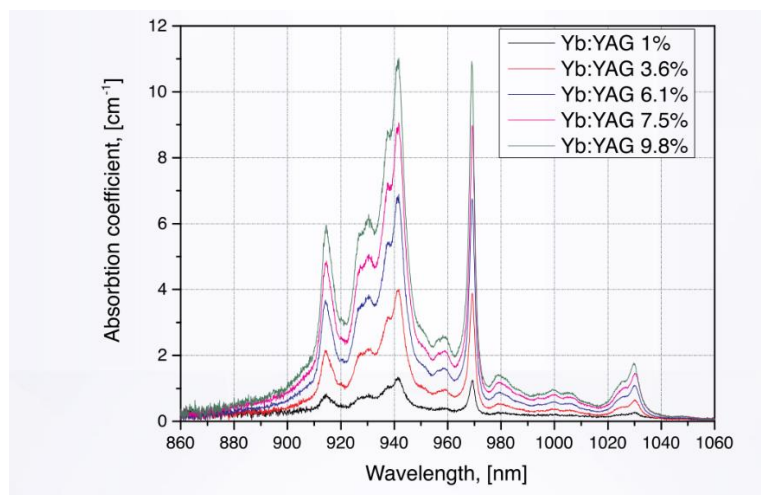


Figure 5. Absorption coefficient of Yb:YAG crystal for different pumping wavelengths. Source: [22]

Between the pump laser diode and the active medium, there is a converging lens with the sole purpose of collimating the pump beam and focusing it on the crystal to maximize the interaction with the gain medium. The lens with a focal length of 15 mm tightly focuses the beam on the crystal, optimizing the spatial overlap at the interaction region. The lens also has an anti-reflection coating at 940 nm to prevent any backscattering from damaging the laser diode.

3.1.2 Gain Medium and Thermal Mounting

As stated, the active gain medium of the laser is a Yb:YAG crystal with a lasing wavelength of 1047 nm. Yb^{+3} is the active ion that is used for doping the crystalline lattice, $\text{Y}_3\text{Al}_5\text{O}_{12}$. This crystal's characteristics fit the requirements for the lasing system as it

boasts a high quantum efficiency, Stokes energy and laser level lifetime and is therefore ideal for an ultrashort pulsed laser [10].

As the crystal absorbs at 940 nm and emits at 1047 nm, the shift between both energies is considered small, this is called Stokes energy. This spectral shift is illustrated in Figure 6. The low Stokes energy indicates a more efficient energy conversion from electrical to optical. Yb:YAG has an intrinsic quantum efficiency of $\sim 90\%$ [10], meaning that the vast majority of photons absorbed by the medium contribute towards stimulated emission. This enhances the system's stability, especially in the case of pulses with high repetition rates.

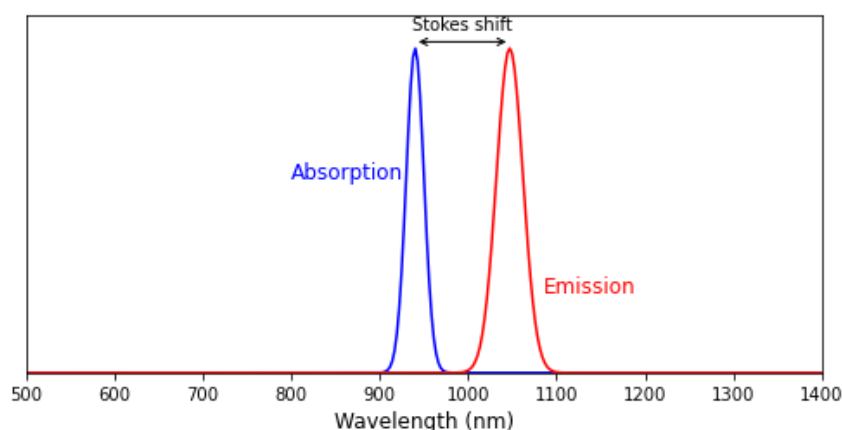


Figure 6. The Stokes shift corresponding to an absorption at 940 nm and an emission at 1047 nm.

A laser level lifetime of ~ 1 ms, comparatively longer than other similar crystals, allows a more efficient accumulation of the population inversion and energy build up for techniques such as Q-switching in picosecond pulse generation. Even though the range for which the laser provides an amplification of light, the gain bandwidth, is relatively limited, at around 5 nm, it is sufficient for picosecond pulses and does not constitute a delimiting factor.

The crystal has a high thermal conductivity ($\sim 10 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), which allows for some heat dissipation, but the continuous operation at high power will overheat it. If heat is accumulated within the gain volume, effects such as thermal lensing will appear [10, 23]. The temperature gradient will induce refractive index variations within the medium, creating an optical lens that will compromise the beam stability and quality. Furthermore, unwanted birefringence can appear, as well as a reduction of the crystal's characteristics, like its quantum efficiency. In extreme cases, the accumulated heat can damage the structure.

An effective thermal design is critical for the correct functioning of the laser system. For this reason, a Peltier module is implemented. This is a thermoelectric device in direct contact with a heat sink, and through active heat transfer, prevents thermal gradients from forming in the material. This module maintains the crystal's temperature at a constant temperature, preventing any deterioration of the active medium.

3.1.3 Laser Cavity

The laser cavity is formed by a flat mirror with a highly reflective (HR) coating that establishes a 99.9% reflection at the operating wavelength and a curved mirror with a radius of 500 mm, which is partially transmissive (20%). They form a linear resonator that surrounds the gain medium, creating a semi-confocal cavity that showcases special properties that further enhance beam confinement [17]. The Radius of the curved mirror is strategically chosen to be double the cavity's length, minimizing lens aberrations and divergence. Figure 7 clearly establishes how a cavity with a length of half the Radius of the curved mirror is within the stability range, whilst also the beam waist reaching its peak, resulting in the setup with the lowest divergence and a symmetric mode [17,18].

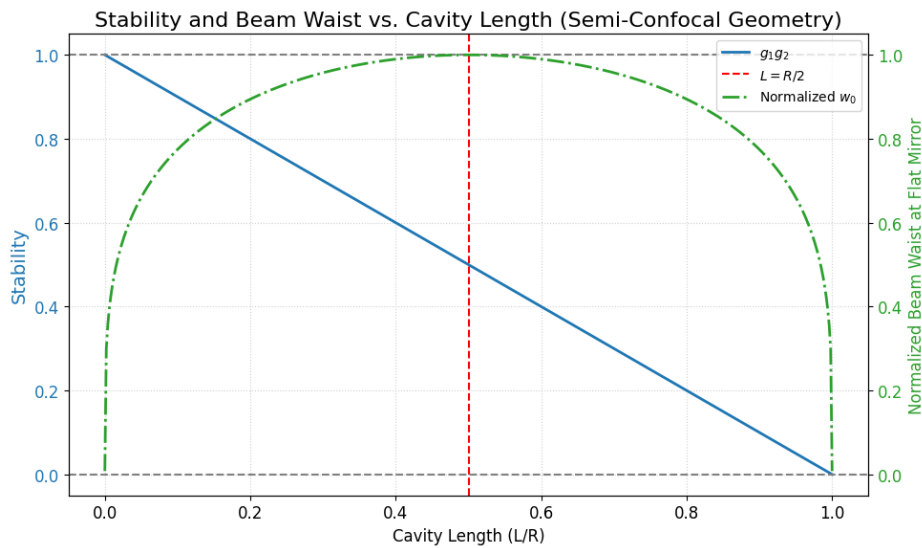


Figure 7. Stability diagram for a semi-confocal laser cavity. It shows the stability parameter and the normalized beam radius as a function of cavity length.

The semi-confocal cavity provides support for well-defined transverse electromagnetic modes and lessens the diffraction losses. Effective beam confinement is the reason for the use of this setup. The combination of both the curved mirror, which reflects diverging light back towards the axis, and the flat mirror, which doesn't, introduces further divergence of the beam in its reflection, resulting in the formation of a standing wave pattern. This ensures a tight confinement that leads to efficient feedback.

The flat mirror is integrated within the Yb:YAG crystal by dielectric coating, facilitating the alignment process as the setup has fewer components. By there being fewer optical surfaces, Fresnel scattering is lessened, increasing intracavity photon lifetime and lowering intracavity losses. Moreover, since the mirror is built into the crystal, it has the perfect axial alignment as it is normal to the optical axis. Angular misalignment and cavity walk-off issues are tackled with this approach. It is important to consider that this configuration offers no tunability, as the mirror can't be rotated. Additionally, if the coating degrades, then the whole crystal must be replaced.

3.1.4 Acousto-Optic Q-Switch

To generate the laser pulses, the model I-M080-2C10G-4-AM3 acousto-optic modulator by *Gooch & Housego* was employed [24]. This modulator presents high spectral compatibility to the lasing system and can also withstand the elevated power generated. The device is also optimized to work at 1047 nm, being a perfect fit for applications that work with solid-state lasers based on Yb:YAG.

The interaction material being crystalline quartz offers unique qualities of thermal stability, damage thresholds superior to $1 \frac{\text{GW}}{\text{cm}^2}$ and diffraction capabilities. These properties allow for efficient performance in regimes of high-intensity picosecond pulses, as damages due to overheating or nonlinear effects are avoided.

Other prominent qualities present are the anti-reflective coating that allows for over 99.4% of transmission, minimizing the optical losses within the modulator, and the active aperture of 2 mm, which accommodates the input light beam without significant distortion. Furthermore, its diffraction efficiency is over 85%, meaning that the vast majority of the energy is deflected towards the first diffraction order, maximising the useful energy transfer and improving the overall performance. The rise time of 113 ns/mm allows for fast modulation of the pulses [24]. For this modulator, the rise time can be calculated as:

$$t_{\text{rise}} = 113 \frac{\text{ns}}{\text{mm}} \cdot 2.0 \text{ mm} = 226 \text{ ns} \quad (3.1)$$

This value limits the temporal resolution of the system. It also determines the period between consecutive laser pulses, as for efficient modulation, this value must be considerably greater than the modulator's rise time. If this condition is not met, temporal overlap and incomplete switching will underperform. Therefore, the rise time not only constrains the maximum repetition rate but also defines the minimum temporal separation required for selective modulation of individual pulses.

A particularity of this model is its working principle, when applying a radiofrequency signal, the refractive index of the quartz varies slightly, diffracting light towards the first order and accumulating energy. In the absence of this RF signal, the optical cavity remains unperturbed, re-establishing beam propagation. In most of the crystals in the market, the working principle is reversed, with the RF signal restoring the optical cavity, allowing for improved energy expenditure. Having said this, the configuration utilized offers several crucial benefits to this laser's configuration.

The aforementioned configuration provides more precise control over the active disruption of the resonant condition and the energy accumulation. This is essential to synchronize the laser pulses with external events and systems. When taking into account subsequent steps of the project, particularly the phase matching of a second harmonic crystal, this level of control proves to be necessary. The approach minimizes the heat exposure towards the crystal, avoiding potential damage and prolonging the crystal's

useful life. Additionally, the system's response becomes faster and more predictable, ensuring high repetition pulses will not suffer from distortion.

The active modulation is electronically regulated by a 555 timer IC in astable configuration that introduces a periodic pulse train at 2 kHz. It generates digital square waves with a period of 500 μ s, as the cyclic relationship is 50%, the pulses used to modulate the acousto-optic crystal have an estimated length of 250 μ s. The timer's output is connected to the stage that controls the radiofrequency generator that powers the acousto-optic crystal. When the 555's output is high level, the RF generator sends an 80 MHz signal to the crystal to temporally decouple the optical resonator. On the contrary, a low-level output ends the acoustic wave propagation.

The inclusion of the 555 timer satisfies the condition imposed by the rise time of the modulator. As calculated in equation 3.1, the rise time of the modulator is 226 ns, and the pulse width of 250 μ s is 3 orders of magnitude lower. Fulfilling the condition ensures that the modulator reaches its maximum diffraction efficiency ($\geq 85\%$) in a reliable and efficient manner.

Given the preceding discussion, the modulator serves as fast commuting optical switch that enables the pulse energy control and modulation. These capabilities allow for a smooth transition towards the following experimental steps, centred around nonlinear frequency conversion and beam characterization.

3.1.5 Pin Holder

The final element of the configuration is a Pin Holder positioned outside the laser cavity performing a critical structural function for the alignment of the system. Its main purpose is to act as high-precision mechanical support maintaining aligned the diverse optical and electrical elements present within the cavity. By establishing clear-cut optical axes, the pumping diode is accurately oriented regarding the Yb:YAG crystal and the rest of the components, ensuring an effective energy flow from the external pumping towards the lasing medium. Moreover, it aids in controlling the stability of the system through the prevention of displacements caused by heat dilatations or external mechanical perturbations. To conclude, the pin holder maintains the integrity of the laser system, helping obtain a robust and reproducible alignment of the components.

3.1.6 Laser Display and Alignment

Figure 8 showcases the arrangement of the laser, and the components previously discussed.

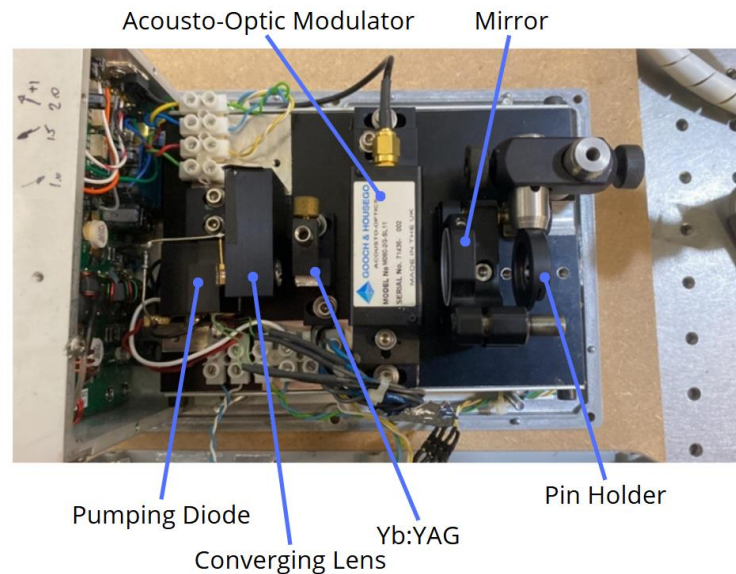


Figure 8. Photograph of the picosecond laser experimental setup, showing the key optical components.

Since one of the mirrors that forms the cavity is integrated into the surface of the active medium crystal, the alignment process is greatly simplified. The input mirror is fixed; therefore, it is only necessary to adjust the output mirror, relative to the pumping diode and the active medium, to achieve optimal lasing oscillations. Therefore, errors due to angular misalignment are partially offset.

In order to achieve a precise alignment that maximizes the output power of the laser, visual references have been added to the mechanical components to facilitate their overall placement and assist in their micrometric positioning. Most notably, in the output coupler, two reference marks are employed: a horizontally oriented line on the support structure that delimits the height of the mirror, and a marked dot on the fine adjustment screws, which must face upward. This configuration enables an effective preliminary alignment.

With respect to the acousto-optic modulator, it was originally aligned with the optical axis of the cavity, ensuring excellent compatibility for basic operation. Nevertheless, the fine adjustment of the incidence angle will boost the system's performance, especially beam stability. It has been determined experimentally that a light inclination of approximately 3 degrees in the horizontal axis drastically improves the overall stability of the optical cavity. Such a configuration induces a partial deviation of the beam trajectory, enhancing the disruption of the cavity's feedback loop. This, in turn, optimizes the intracavity energy storage, leading to a more effective optical feedback and laser operation.

The modulator is mounted with a clamping screw in the horizontal plane. To enable the inclination angle adjustment of the acousto-optic modulator it is necessary to loosen the screw. Once loosened, the micrometric actuator can be utilized to gently displace the modulator and observe the system's response. The optimal 3-degree alignment is confirmed once a peak in the output power is observed.

3.2 Technical Specifications

3.2.1 Average Power

Precise measurement of the laser's average output power is an indispensable requirement towards understanding its capabilities and enabling further characterization. This magnitude allows for a plethora of things; mainly, it serves as an excellent indicator of the laser system's performance, allowing verification whether the technical specifications of the system are met. Additionally, it serves as a quite effective manner to align the optical cavity, as maximizing the output power directly correlates with a more precise cavity configuration. During the alignment phase, this metric was consistently utilized to achieve and pinpoint the optimal conditions and positioning of the diverse optical elements.

Checking the suitability for certain applications and other elements is also crucial, as, if needed, power dissipators must be used to avoid any damage to the measuring devices or any of the other components in subsequent configurations. Lastly, characterising this parameter is a safety requirement. Risk evaluations and safety regulations directly depend on the value of the average output power, as the value gives an idea of the dangers of exposure to the laser beam.

To measure average power, due to its relevance, it is required to utilize an adequate sensor that responds to the specific characteristics of the laser. For this purpose, the thermal sensor LASERPOINT A-10-D12-HP was employed, being the most optimal and available option within the laboratory equipment. To read the output signal, the sensor was connected to the power meter LPT-PLUS 2, from the same manufacturer [25]. The response time, measured from 0 to 90%, is 0.8 seconds. This value leads to a very accurate approximation of the beam's dynamics. The response time fails to be ideal as the high repetition rate of the laser limits the reading; however, the present limitation is not notable enough to constitute the need to purchase a different measuring instrument.

3.2.1.1 Configuration of the Measuring System

The following procedure was used to ensure a reliable and stable measurements of the data, as the device parameters can wildly affect the readings if not optimised to the specific laser system's characteristics:

1) Wavelength Calibration

The thermal sensor's sensitivity is wavelength-dependent, so in order for an accurate power reading, the sensor must be calibrated at the working wavelength, in this case being 1047 nm. The parameter is easily changed in the tactile menu of the device, inside the "Wavelength" section.

2) Response Mode

Even with the somewhat underwhelming response time of the device, its inherent slow nature can be somewhat improved by changing the response mode of the system. The

“Acceleration” option, withing the “Measure” menu, applies an algorithm to partially offset the sensor’s thermal inertia to improve the time it takes to stabilize the signal. Optimizing the response mode is key to reduce any potential signal degradation.

3) Acquisition Mode

In the menu “Statistics”, it is possible to select different measurement methods, of particular interest for this system are the modes “Continuous” and “Single”. The first mode is used for real-time measurements of the average power utilized for dynamic alignment and adjustment of the beam and the optical components. The latter mode works by doing an average measurement over an integration interval defined by the user. Setting a 2-second time interval allows for a more stabilized measurement with less appreciable fluctuations.

Of vital importance is resetting the sensor before every measurement given that it will save and apply the changes to the configuration, as well as providing a reading uninfluenced by the hysteresis of the thermal signal stored from past uses.

After careful calibration of the system, adjusting for an unfiltered beam to enter the sensor, a reading of **240 mW** was registered. Even if it's low, the ultrashort characteristics of the laser will ultimately accomplish a high enough peak power for the subsequent applications.

3.2.2 Pulse Parameters

To fully understand the laser system, it is imperative to characterize the pulses, since it will determine the laser’s behaviour and suitability for potential applications. Due to the fact this is a pulsed and not a continuous laser, energy is concentrated into extremely brief time intervals. This, in turn, sparks the need for a complete analysis of the spectral and temporal parameters of the pulse. The following parameters were determined experimentally.

Repetition frequency (f_{rep}). Defines the number of pulses emitted per second, being related to the average power. A compromise between the repetition rate and the energy per pulse is reached to avoid any cumulative thermal damage in measurement devices or optical elements. Repetition frequency is controlled by the laser oscillator and regulated by the 555 timer IC in normal operation. It should be noted that the configuration is flexible permitting the repetition frequency to be modulated by way of connecting a radiofrequency generator to the laser.

To achieve an experimental value, the DET08CFC photodetector from *Thorlabs* was employed [26]. Within the available measuring devices, this photodetector presents itself with a wide spectral range (1047 nm falling within it) and a high velocity response time. A 5 GHz bandwidth indicates the maximum frequency at which the photodetector can detect changes in the signal without distortion. There exists a relationship between the bandwidth and the rise time of the photodetector given by the formula [26]:

$$t_{\text{rise}} \approx \frac{0.35}{f_{\text{BW}}} \quad (3.2)$$

For the DET08CFC with 5 GHz bandwidth, the rise time is:

$$t_{\text{rise}} \approx \frac{0.35}{5 \cdot 10^9} = 70 \text{ ps} \quad (3.3)$$

Such a rise time indicates that optical structures with temporal structures of 70 ps or more can be resolved with high fidelity.

Furthermore, of the range of fast photodetectors in which this model is found, DET08CFC has the highest responsiveness to the operating wavelength. As seen in Figure 9 from the operating data provided by Thorlabs, at 1047 nm, it has an approximate response of 75%. This value guarantees an efficient conversion of the incident optical energy from the laser into the electrical signal that the device is capable of measuring. Such a high responsivity value minimizes the loss of optical information.

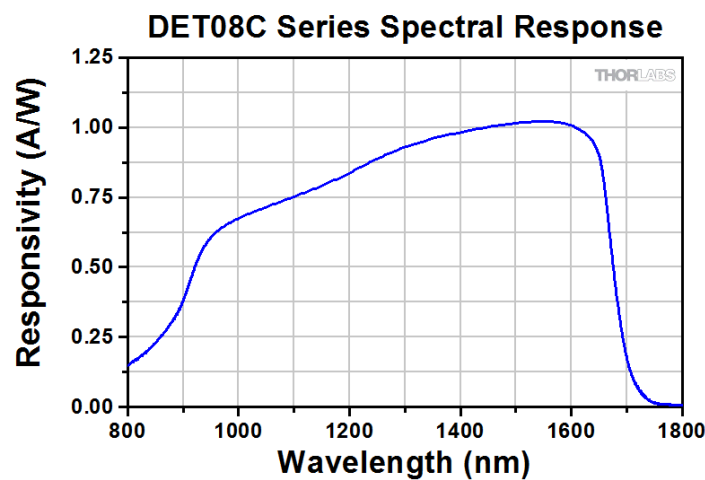


Figure 9. Spectral responsivity curve of the Thorlabs DET08CFC photodetector. Source: [26]

The photodetector connected to an oscilloscope was adjusted to receive the laser beam. Due to its characteristics, it can withstand a 100 mW power peak, meaning it is necessary to introduce a power limiter into the beam path. In Figure 10, the image obtained is represented. The regular signal peaks clearly show a pulse train of pulses distanced by 2 oscilloscope divisions. As the time base seen in the figure is 250 $\mu\text{s}/\text{div}$, the pulses are spaced by 500 μs , which indicates a **2 KHz** repetition frequency; therefore, it is concluded that the 555 timer IC correctly modulates the laser.

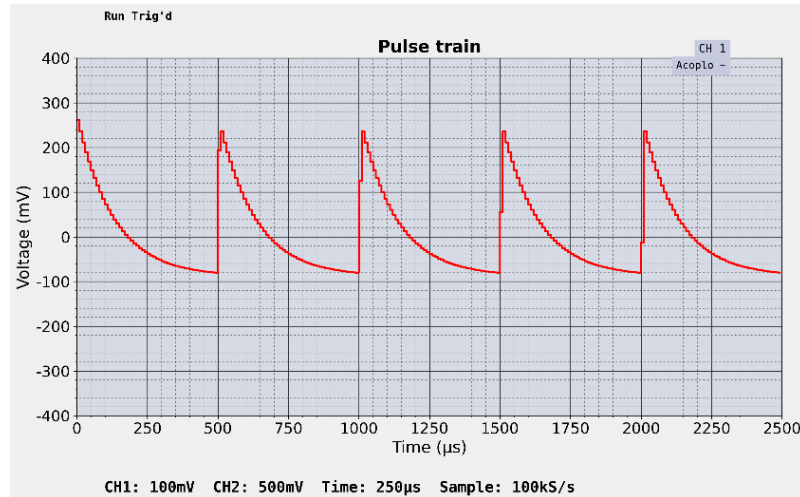


Figure 10. Oscilloscope trace showing the laser pulse train. The time base is 250 $\mu\text{s}/\text{div}$.

FWHM (Full Width at Half Maximum). The FWHM is employed as a means of characterising the effective width of the pulse or the spectrum. In a temporal context, it provides a direct measurement of the duration of the pulse. Meanwhile, in a spectral domain, it defines the frequency range for which the pulse contains an intensity superior to half its maximum value. This metric assesses the quality of the temporal compression of the pulse as well as determines other parameters.

For spectrally characterizing the laser, a Spectral Optic Analyzer (OSA) was employed. In particular, the model of the OSA was the *Yokogawa AQ6373B* [27]. For a setup that maintained the integrity of the OSA and the validity of the results, a series of critical steps were taken. Firstly, the system was calibrated and stabilized, which entailed turning on the machine and following the manufacturer's instructions to perform an internal calibration of the system. A correct wavelength and power reference is guaranteed by this calibration. Consequently, the equipment was stabilized for at least an hour, for which under no circumstances a measurement must be done; this avoids any thermal drift errors as well as prepares the system for future measurements.

In parallel to the stabilization of the OSA, the alignment of the laser was performed with the objective of coupling the beam with a single-mode fibre. Taking into account that the laser generates ultra-short, high-powered pulses, optical attenuators were introduced to limit the incident power. Moreover, a convergent lens was added in the beam path to obtain a laser spot with a symmetrical and circular profile. A spot with a higher quality led to a better and more direct coupling, and the addition of the lens concentrated the beam and counteracted the dispersive nature of the laser.

An important precaution that had to be taken into account was the fibre entrance since it acts as a partially reflective surface. Given that the beam could be reflected towards the laser cavity and generate unwanted feedback or irreversible damage to the mirrors or crystal components, measures were taken. A slight angular misalignment of the optic path towards the OSA was used to mitigate risks as well as a continuous measurement of the reflected power.

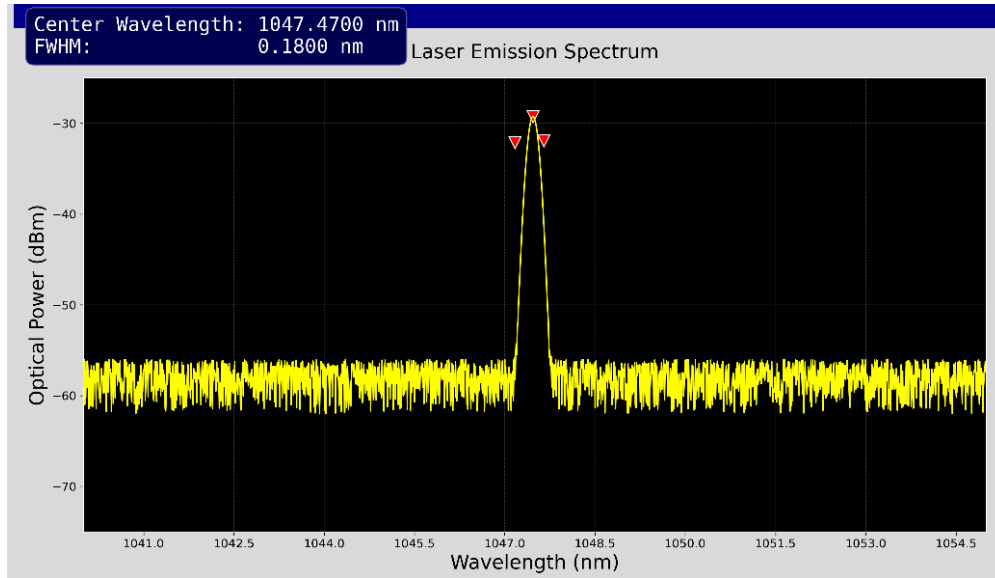


Figure 11. Optical spectrum of the laser output measured with the OSA and markers positioned 5dB below peak value.

Once everything was set up, the laser's spectrum was visualized, allowing for the characterization of its Gaussian form and FWHM. In Figure 11, a Gaussian profile can be clearly seen, as expected, since this is characteristic of stable mode-locking lasers. This spectral profile shows a constant phase relationship between the laser modes, implying a high temporal coherence. This, in turn, allows for the generation of well-defined temporal pulses. Having a Gaussian spectral shape entails that the Fourier transform is also Gaussian. The combination of that, and the lack of chirp in the pulse, are indicative that the pulse is closing in to be transform-limited, meaning the configuration is near ideal conditions having an ultrashort pulse whose temporal duration is the minimum possible for the given spectral width.

From Figure 11, the markers were positioned at the peak of the pulse and 5 dB below to correctly gauge the FWHM. The image indicates the laser has a FWHM of **0.18 nm**, being a narrow spectral width characteristic of a stable mode-locking solid-state Q-switch laser source.

Spectral width ($\Delta\nu$). Through the Fourier relation, it is associated with temporal coherence and pulse duration. Per this relation, it is shown that the tendency is that the shorter the pulse, the bigger its spectral width. This is important in nonlinear applications such as frequency conversion in optical crystals. Nonlinear processes are intensity-dependent, so a shorter pulse will provide, for a given pulse energy, a higher peak power. Also, a wider spectrum will better match the limited phase-matching bandwidth of a nonlinear crystal. In an ideal pulse, the relation between temporal duration and spectral width is defined as:

$$\Delta\nu \cdot \tau_p \geq K \quad (3.4)$$

Where τ_p is the pulse duration, and K is a value that depends on the pulse shape. As discussed per figure 11, the shape of the pulse is Gaussian; therefore, the value of K is

$K \approx 0.44$ [18]. Equation 3.4 allows for the evaluation of whether any chirp or dispersion is introduced in the pulse via the laser system.

To accurately determine the spectral width, once again, the markers were positioned accordingly at the widest part of the pulse profile, as seen in Figure 12. From this, it was determined that the spectral width of the laser is **1.5 nm**.

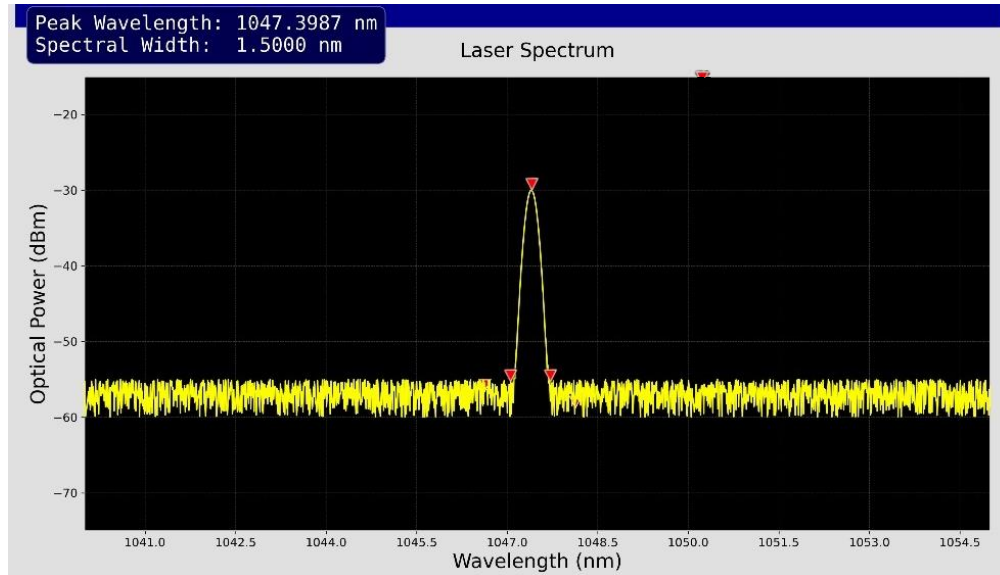


Figure 12. Optical spectrum of the laser output measured with the OSA and markers positioned at the widest part of the beam.

Pulse duration (τ_p). The temporal interval in which the pulse is emitted will determine the temporal resolution of the system. Faster temporal dynamics in ultrafast spectroscopy can be resolved by having a shorter laser pulse. For the same pulse energy, the pulse duration is inversely proportional to peak power. Shorter pulses translate to higher power peaks, ideal for the subsequent nonlinear configurations.

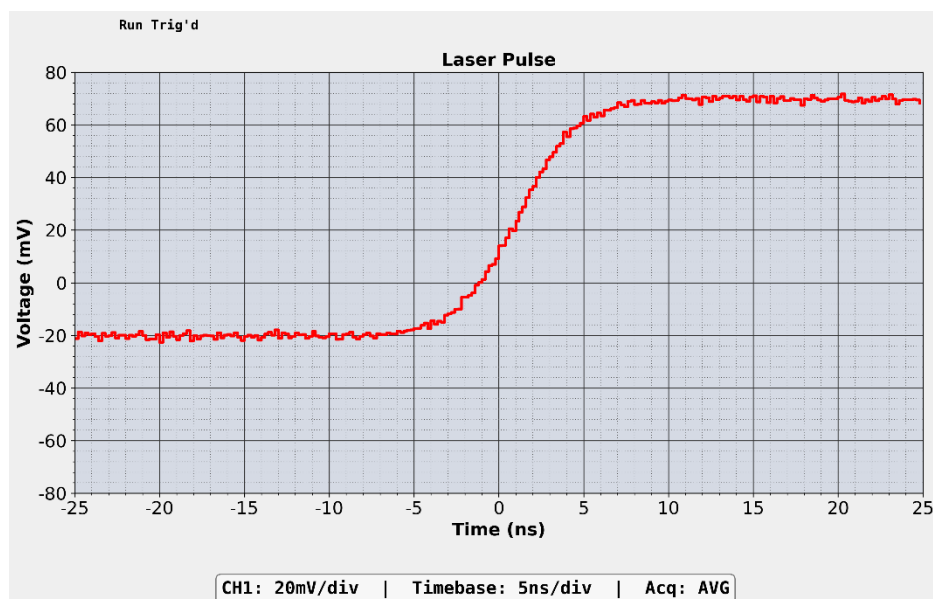


Figure 13. Oscilloscope trace of a single laser pulse.

In Figure 13, the oscilloscope shows one pulse whose shape isn't symmetric and describes a curve for which the slope gradually decreases as the pulse evolves. As a result of this image, it is concluded that the pulse duration is being limited by the bandwidth of the oscilloscope and/or photodetector. From equation 3.3, it is disclosed that the temporal duration has to be far smaller than 70 ps.

As a means of inquiring an exact measurement for this parameter, the values obtained from the OSA were used. The OSA has a greater resolution than the photodetector, leading to an accurate measurement, not limited by its response time. From Figure 11, and employing the Fourier relationship from equation 3.4, as the pulse is shown to be transform limited, the following procedure is done:

$$\tau_p = \frac{0.44}{\Delta\nu} \quad (3.5)$$

The relationship between frequency and wavelength is defined by:

$$\nu = \frac{c}{\lambda} \quad (3.6)$$

The spectral width in Hz is obtained through equation 3.7, where c is the light velocity constant and $\Delta\lambda$ is the FWHM.

$$\Delta\nu = \frac{c}{\lambda^2} \cdot \Delta\lambda \quad (3.7)$$

Substituting the corresponding values gives a spectral width of $\Delta\nu \approx 49.2$ GHz. Entering equation 3.7 into 3.5 gives a pulse duration value of $\tau_p \approx \mathbf{9 \text{ ps}}$. This value confirms the laser to be a picosecond laser, and that the Q-Switching was thoroughly optimized to obtain such an ultra-short pulse. It is important to highlight that this value represents the theoretical minimum duration (transform limit) for the measured spectral width. Q-switched systems often exhibit some degree of temporal chirp, which means the actual pulse duration may be slightly longer than the ideal calculated value.

Energy per pulse (E_{pulse}). Represents the total energy contained in one laser pulse. The energy per pulse is usually defined by:

$$E_{\text{pulse}} = \frac{P_{\text{avg}}}{f_{\text{rep}}} \quad (3.8)$$

Characterising this value is crucial for second harmonic generation as the efficiency of frequency conversion depends on the quantity of energy administered per area and time. In SHG, as the response towards the energy is not linear, a little variation of the energy can vastly affect the conversion efficiency. Additionally, the energy per pulse is important to maintain a safe operating regime and avoid damage to the measurement devices or other optical elements.

From equation 3.8, and substituting the values obtained in previous subsections, a value of $E_{\text{pulse}} = \mathbf{120 \text{ }\mu\text{J}}$. Such a high value for a picosecond laser satisfies conditions for second harmonic generation, even without the need for amplification. This is due to the fact that the energy will most likely surpass the nonlinearity threshold of nonlinear

crystals. It is also relevant to highlight the importance of maintaining control over the pulse power and energy, as it can easily damage other components.

Peak Power (P_{power}). It is the maximum instant power during one pulse. In ultra-short picosecond lasers, very high peak power is reached even with moderate average power, this is because of how this parameter is defined for Gaussian pulses:

$$P_{\text{peak}} = \frac{E_{\text{pulse}}}{\tau_p} \quad (3.9)$$

Performing a quick substitution, results in a calculated peak power of $P_{\text{peak}} \approx \mathbf{13.33 \text{ MW}}$. Such a high value, in the megawatt range, further proves the potential of the laser. All the considerations taken in the energy per pulse subsection are pushed further as this value confirms the laser's ability for SHG, as well as the precautions needed for handling such high-power peaks.

3.2.3 Polarization and Wavelength

For the last part of the beam characterization, the polarization and the wavelength of the laser will be assessed. From Figure 11, the peak clearly showcases the central functioning wavelength of the laser, that being, as continuously mentioned, **1047 nm**. The polarization is key, as for SHG, the optical axis of the nonlinear crystal must be aligned with the laser's polarization to achieve phase-matching conditions. To measure the polarization, a simple approach was taken.

A linear polarizer is an optical element that absorbs any electrical field component that is orthogonal to its transmission axis, allowing only transmission for the components parallel to said axis. The linear polarizer utilized was a linear polarizing film due to its simplicity, quickness, and effectiveness. It was carefully inserted into the beam path to ensure there was no angular misalignment that would cause an error. Its working principle is illustrated in Figure 14.

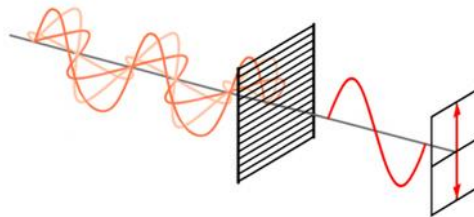


Figure 14. Operation of a linear polarizing filter, which only allows the electric field component parallel to its transmission axis to pass. Adapted from [9].

The A-10-D12-HP sensor was placed behind the polarizer to register the transmitted power. To assess the polarization, a first measurement was done with the film's axis aligned vertically; afterwards, the film was rotated 90° to register a measurement with the axis aligned horizontally. Vertical axis alignment resulted in nearly perfect transmission, whereas horizontal alignment registered a weak signal in the sensor. The method

validated the direction of the transversal electrical field, that being a **linear vertical polarization**.

After having characterized the beam parameters, the findings are collected in Table 3.

Parameter	Value
Wavelength	1047 nm
P_{avg}	240 mW
E_{pulse}	120 μ J
P_{peak}	13.33 MW
τ_p	9 ps
f_{rep}	2 kHz
$\Delta\nu$	1.5 nm
FWHM	0.18 nm
Polarization	Linear/Vertical

Table 3. Summary of the characterized parameters of the fundamental laser beam.

3.3 Laser Modulation

To modulate a Q-switched pulsed laser, the timing and process in which the energy stored within the laser's active gain medium (a Yd-doped crystal) is released must be meticulously controlled. For this particular configuration and laser system, the modulation can be achieved by way of two distinct methods. The previously discussed 555 timer IC is one option that modulates the acousto-optic modulator using electrical pulses at a frequency rate of 2 kHz. On the other hand, an RF signal generator can also be coupled to the laser system to modulate the Q-switch. This option allows for precise control of the frequency repetition and therefore has control over the energy and power of the pulse.

Experimentally, it was observed that for repetition rates exceeding 2 kHz, where the period between pulses was shortened, the ability for the active medium to reach full population inversion was limited. This means that the energy stored within the active medium does not reach its peak value before laser emission, therefore reducing the pulse energy. This in itself represents a limitation of the pumping mechanism and the active medium. In Figure 15, this phenomenon is showcased. In the first plot, it is shown how the 5 kHz repetition rate does not accomplish a full population inversion due to the shorter interval between emissions. As a result, the lack of stored energy results in an inferior intensity emission as shown in the second plot.

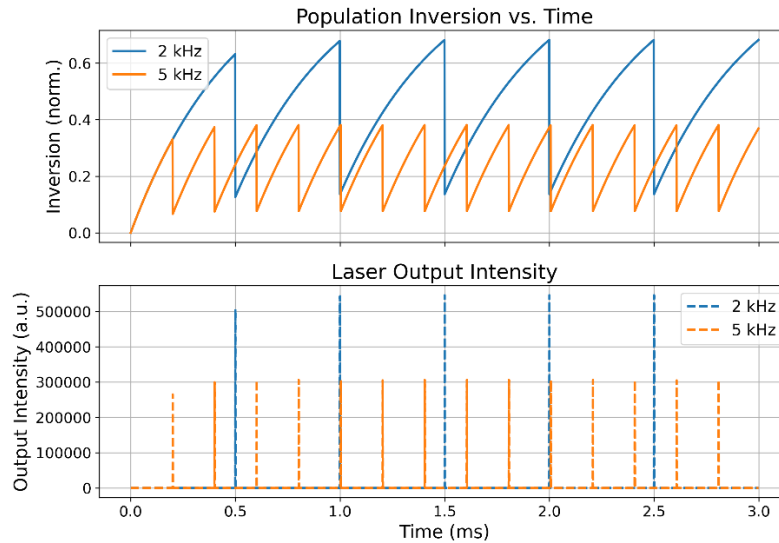


Figure 15. Simulation of the effect of repetition rate on laser performance.

Furthermore, when using the radiofrequency signal generator, the amplitude of the drive signal must exceed 4.2 V to ensure proper operation of the acousto-optic modulator. Amplitudes below this threshold suppress laser emission as the signal fails to induce a significant change to the refractive index of the acousto-optic crystal. To ensure effective Q-switching, an empirical value of 5 V was concluded to be an optimal level to guarantee consistent and stable modulation.

Applying no signal whatsoever led to continuous-wave (CW) operation, meaning the laser was in an unmodulated state. Alternatively, if the need to completely inhibit laser emission arises, a direct current signal with an amplitude above 5 V can be applied.

The selection between the two methods depends primarily on the application requirements. The 555 timer serves as a high-powered, practical solution utilized in situations where the pulse energy is relevant. On the contrary, the RF generator offers great flexibility and accuracy, ideal for situations where precision is sought for. Transitioning between both approaches is done so via a switch on the electronics control box.

3.4 Beam Profile

3.4.1 *BeamMaster Software*

Once having defined the beam's static characteristics, to further understand laser operation, a quantitative analysis on the spatial expansion of the beam propagated in open air, was performed. Measurements were done from a starting distance of 20 cm to 1 meter in intervals of 10 cm. Special interest was taken in key positions such as the 20, 50, and 100 cm mark. By comparing the real beam behaviour with an ideal Gaussian distribution, the stability and symmetry during propagation are evaluated.

The *BeamMaster* software was utilized to perform the measurements, as this tool allow for straightforward appraisal of the intensity profile for both orthogonal profile cuts: horizontally and vertically [28]. For each distance, the program analysed for both

positions the beam diameters for three levels of relative intensity from the maximum: 80%, 50%, and 13.5%. The last value is particularly interesting as it corresponds to the standard value that defines the beam radius in Gaussian optics. This is considered as the beam's effective size, since at the 13.5% level the intensity falls to $1/e^2$ of its peak value. The radius that encloses that region is where most of the beam's energy is concentrated. From the diameters obtained, the program also made a comparison with the ideal values of a Gaussian function to obtain a Gaussian correlation (the fidelity of the profile towards an ideal propagation).

Other major parameters the software computes are from the fitted ellipse. This ellipse is mathematically adjusted to the intensity profile to give a clear representation of beam size, shape, and orientation. With the objective of viewing the tendency of astigmatism or beam asymmetry during propagation, the axis of the ellipse and the inclination angle are acquired.

<i>Profile</i>	<i>Intensity (%)</i>	<i>Measured Diameter (μm)</i>	<i>Adjusted Diameter (μm)</i>	<i>Ellipse Axis (μm)</i>	<i>Orientation ($^\circ$)</i>	<i>Centroid (μm)</i>
<i>V (Horizontal)</i>	80%	295.4	333.0	1107 (major), 711(minor)	114	$X=129.7$ $Y=1.0$
<i>V (Horizontal)</i>	50%	565.3	578.7			
<i>V (Horizontal)</i>	13.5%	1079	983.6			
<i>W (Vertical)</i>	80%	225.4	241.2			
<i>W (Vertical)</i>	50%	432.2	426.2			
<i>W (Vertical)</i>	13.5%	776.9	724.3			

Table 4. Beam profile parameters measured at a distance of 20 cm using BeamMaster software.

<i>Profile</i>	<i>Intensity (%)</i>	<i>Measured Diameter (μm)</i>	<i>Adjusted Diameter (μm)</i>	<i>Ellipse Axis (μm)</i>	<i>Orientation ($^\circ$)</i>	<i>Centroid (μm)</i>
<i>V (Horizontal)</i>	80%	1118	1117	4308 (major), 3673(minor)	18	$X=34.9$ $Y=-10.3$
<i>V (Horizontal)</i>	50%	1994	2057			
<i>V (Horizontal)</i>	13.5%	3708	3497			
<i>W (Vertical)</i>	80%	1605	1448			
<i>W (Vertical)</i>	50%	2581	2552			
<i>W (Vertical)</i>	13.5%	4277	4337			

Table 5. Beam profile parameters measured at a distance of 100 cm using BeamMaster software.

Tables 4 and 5 represent the obtained experimental values from the BeamMaster software at 20 cm and 100 cm, respectively. This data confirms that the beam expands as

propagation distance increases, which is consistent with the behaviour of a Gaussian beam. At the 20 cm mark, for each level of profile intensity measured the diameters of the beam are inferior to 1.1 mm. As expected from Gaussian beam theory, at the 100 cm mark, the diameters have expanded, reaching values above 3.5 mm in both vertical and horizontal axes. This distinctive difference reflects a considerable divergence with high lateral dispersion.

The Gaussian correlation is remarkably strong, even if there are light discrepancies attributed to imperfections such as astigmatism or asymmetry within the beam. A ~90% correlation is maintained throughout every position, showing a slight anisotropy because of the slightly worse correlation of the vertical profile.

Furthering the previous argument, the ellipticity of the fitted ellipse's axes widely increases with propagation distance, in particular, this phenomenon is present in the vertical plane. At 20 cm the major axis measures 1107 μm , reaching 4308 μm at the 100 cm position. This representation of the relationship between the major and minor axes of the ellipse strengthens the previous proposal of an isotropic beam propagation.

Additionally, the orientation of the fitted ellipse suffers an appreciable change going from 114° at the nearest position to 18° at its furthest. A progressive rotation of the beam with distance is deduced. Notably, starting from the 50 cm mark, the orientation stabilizes around 18°, which happens due to the decrease of the losses caused by the initial optical coupling.

From the analysed data, it is concluded that the beam expansion must be controlled for applications that require a collimated beam with little lateral dispersion, such as fibre inscription. The pulsed laser is coherent with the Gaussian beam theory as the appreciable spatial expansion grows accordingly. To mitigate divergence collimation, focusing optical systems need to be incorporated into the optical path.

3.4.2 Quantitative Analysis

Based on the experimental results, other prominent parameters are calculated to evaluate beam quality and suitability for different applications. The angular divergence, beam waist, ellipticity, and centroid stability are all considered and discussed.

Angular divergence (θ). Another metric that characterizes the broadening of the beam from the optical source. Defined as the difference in radius over the difference in positions, as shown in the following equation:

$$\theta \approx \frac{w(z_2) - w(z_1)}{z_2 - z_1} \quad (3.10)$$

In equation 3.10, $w(z)$ represents the beam's radius at the position z . To calculate the divergence, z_2 and z_1 are 100 cm and 20 cm, respectively; meanwhile, for the radius, the diameter for each position for 13.5% intensity (per international standard) is obtained from Tables 4 and 5. An angular divergence of $\theta \approx 1.64$ mrad for the horizontal axis, and $\theta \approx 2.19$ mrad for the vertical axis, was obtained.

Once again, the results confirm the existence of a certain degree of astigmatism due to a faster expansion on the vertical axis of the beam. This behaviour will be taken into account when introducing optical elements in the optical path.

Beam waist (w_0). From having the laser's waist in the near region of the 20 cm measurement point, an estimation of the minimum radius is given by the beamMaster software.

From the sweep performed to determine the beam diameter, it was experimentally verified that the point of the smallest beam size was found around 20 cm. Being a Gaussian pulse, it is measured at 13.5% intensity. Therefore, the radius of lowest intensity is estimated to be $w_0 \approx 539.5 \mu\text{m}$ horizontally, and $w_0 \approx 388.4 \mu\text{m}$ vertically. From the values in Tables 4 and 5, the corresponding diameters were utilized and halved to obtain the radius.

Ellipticity (ϵ). Since the beam is not circular, as has been rigorously verified previously, it can be described by ellipticity. This allows us to determine how deformed the laser cross-section is. This ratio is defined as the quotient of the beam diameters at an intensity of 13.5%, which measures the physical size of a Gaussian beam.

$$\epsilon \approx \frac{D_V}{D_W} \quad (3.11)$$

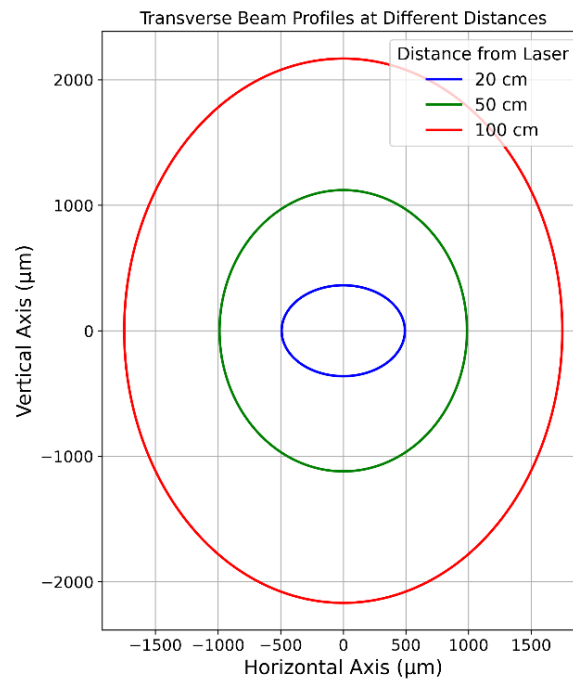


Figure 16. Evolution of the elliptical beam profile at different propagation distances (20 cm, 50 cm, and 100 cm).

Substituting in formula 3.11 gives an ellipticity of $\epsilon = 1.39$, $\epsilon = 0.96$, and $\epsilon = 0.87$ for 20, 50, and 100 cm, respectively. Figure 16 portrays how the ellipse expands and how, at the beginning, the beam is wider horizontally. However, as the propagation distance increases, it eventually rotates and is slightly inverted at the end. This inversion is shown as the widening of the vertical axis compared to the horizontal axis.

Centroid Stability. The beam centroid is the central intensity point of the beam profile, allowing for the assessment of the effective spatial position of the beam and helping with its alignment and stability. From Tables 4 and 5 and the registered position of the centroid for each measurement distance, a standard deviation of $\pm 68.8 \mu\text{m}$ on the horizontal axis and $\pm 4.5 \mu\text{m}$ on the vertical axis was calculated. This exhibits a lateral variation in the system that can be attributed to the rotation effect the profile suffers, as seen previously. The centroid variation on the horizontal plane could represent a limitation for applications with submicron sensitivities. On the other hand, the other axis shows great stability in the intensity of the profile.

3.5 Safety Regulations

Having defined and characterized the laser system, a rigorous assessment of the associated risks can be carried out, along with the adoption of protective measures that comply with current international standards. In this context, the IEC 60825-1:2014 standard [29] establishes the criteria for classifying laser products based on parameters such as emitted power, wavelength, and beam accessibility.

By emitting high-energy pulses in the near-infrared region (1047 nm), reaching peak powers on the order of several megawatts, and in accordance with the standard, the system is classified as a Class 4 laser. This type of device poses a high risk of ocular and skin damage, as well as a potential for fire or deterioration of sensitive materials exposed to the beam.

This classification and the associated risks justify the need for the system's assembly, alignment, and operation to be carried out exclusively under controlled conditions, following strict safety protocols. The implemented protective measures require the use of certified laser safety goggles with optical densities appropriate for the wavelengths in use (1047 nm and 523 nm). Additionally, screens or barriers must be employed to prevent the accidental propagation of radiation outside the working area, along with proper signage of the environment using warning pictograms and equipment labelling in compliance with IEC 60825-1 [29].

These measures not only minimize the risks involved in operating the laser system but also create a safe working environment. Following these measures ensures the system's compliance with legal and regulatory requirements, applicable to the use of high-power laser sources in research settings.

Chapter 4. Implementation of a Multiwavelength Laser

4.1 Crystal Election

Second harmonic generation is heavily dependent on the nonlinear crystal utilized; hence, special interest was taken in selecting a material whose characteristics would best couple to the previously characterized lasing system. The conversion efficiency greatly relies on the optical quality and the phase coincidence between the crystal's fundamental and harmonic waves. Ultimately, an LBO crystal from *Eskma Optics* was chosen as the most optimal fit for the laser setup [30]. The discussion of the physical-optical and geometric properties of the crystal is specified to justify this selection.

4.1.1 Geometrical Properties

The specific geometry of the crystal helps maintain the laser beam's spatial integrity when undergoing nonlinear interactions.

Crystal Dimensions. The dimensionality was chosen as a compromise between cost and effectiveness. The conversion efficiency and beam quality are heavily dependent on the geometry. The crystal was chosen with dimensions of 5x5x10 mm (width × height × length).

The length of the crystal (10 mm) represents the propagation axis and determines the amount of nonlinear interaction between the fundamental and the generated beam. A 10 mm crystal offers an efficient conversion greater than smaller configurations, as efficiency scales quadratically with length ($\eta \propto L^2$) [20]. Even though the length is bigger, the angular walk-off introduced is still manageable; the progressive separation induced between the beams is defined by:

$$\Delta x = L \cdot \tan(\rho) \quad (4.1)$$

Where ρ is the walk-off angle, which for an LBO crystal is typically between 0.5° to 1.5° (considerably lower than other nonlinear crystals). Therefore, the resulting displacement is around $\Delta x \approx 87 - 287 \mu\text{m}$.

The transversal area (5x5 mm) prevents the beam from interacting with the edges of the crystal to avoid diffraction effects or scattering losses. For a beam diameter of 0.766 mm (extracted from Table 4 for 13.5% intensity), the crystal is more than 6 times larger than the beam width, assuring a reliable light coupling.

Flatness. This indicates the surface deviation from an ideal flat source [20]. The crystal has a value of $\lambda/8$ at 633 nm (79 nm), even though that is not the functioning wavelength of the laser, the absolute error is wavelength independent. In this case, the wavefront suffers a maximum distortion of $1/13^{\text{th}}$ of the wavelength (1047 nm). Having such a smooth surface maintains a good coupling relationship for the phase between the fundamental and the second harmonic wavelengths.

Parallelism and Perpendicularity. The crystal displays a parallelism between its opposite faces of < 20 arcsec ($\approx 0.0056^\circ$), which is a strict condition that guarantees the incident laser beam and the generated second harmonic beam alignment are upheld, so beam walk-off issues do not arise. Otherwise, the crystal displays a perpendicularity between its adjacent faces of < 5 arcmin ($\approx 0.083^\circ$). Although the perpendicular condition is not as demanding as the parallelism, it is still a strict condition that prevents appreciable walk-off losses.

Angle and Aperture Tolerance. Angle tolerance indicates the precision of the crystal's cut with respect to its crystallographic axes; the LBO has a value of < 30 arcmin ($=0.5^\circ$). This value is critical for high precision applications. A lack of angular precision results in a considerable loss of conversion efficiency. Aperture tolerance is the dimensional precision of the active area of the crystal, being ± 0.1 mm. This parameter is essential to ensure the fundamental laser beam does not interact with the edges of the crystal. Since the crystal's nominal aperture is in the range of 5 mm and the beam waist is $776.9 \mu\text{m}$, even with a ± 0.1 mm tolerance, the minimum aperture will still comfortably fit the beam without any underlying problems.

Clear Aperture. Specifies that at least 90% of the transversal section of the crystal is free from impurities, minimizing losses and damages due to energy concentration in defects. While commercially available crystals usually offer around an 80% clear aperture, this crystal stands out as its 90% value is ideal for the high-powered laser system.

4.1.2 Physical-Optical Properties

Optic Transparency range. Having a range of (155-3200 nm), these values show that the wavelength for which the crystal has high transmission engulfs both the fundamental wavelength (1047 nm) and the second harmonic (523.5 nm), meaning absorption losses are minimized.

Anti-reflective coating. The coating was custom ordered at 1047 nm and 523.5 nm specifically for the high-power Yb:YAG laser system. *Eskma*'s coating guarantees that for both key wavelengths of the SHG process, the reflection losses are reduced below 0.2%.

Refractive Index. Refractive index is wavelength dependant, *Eskma* in the specifications sheet provide the equation to determine this parameter [29]. Knowing the refractive index, the orientation of the cutting angles of the crystal can be calculated to achieve optimal Type I phase-matching. The equations are given by [29]:

$$n_x^2 \approx 2.4542 + 0.01125/(\lambda^2 - 0.01135) - 0.01388 \lambda^2 \quad (4.2)$$

$$n_y^2 \approx 2.5390 + 0.01277/(\lambda^2 - 0.01189) - 0.01849 \lambda^2 \quad (4.3)$$

$$n_z^2 \approx 2.5865 + 0.01310/(\lambda^2 - 0.01223) - 0.01862 \lambda^2 \quad (4.4)$$

For equation 4.2, 4.3 and 4.4, λ is in micrometres. The resulting refractive indexes are shown in Table 6.

	n_x	n_y	n_z
1047nm	1.5650	1.5908	1.6057
523.5nm	1.5790	1.6071	1.6222

Table 6. Calculated refractive index for the LBO crystal at the fundamental and second harmonic wavelengths.

Phase-Matching and Angular Orientation. For the operation wavelength, the crystal offers a non-critical type I phase coincidence (NCPM). In order to achieve the phase-matching Type I, the condition $n_{\text{eff}}(\omega) = n_{\text{eff}}(2\omega)$ (obtained from equation 2.7) must be satisfied. In a Biaxial crystal such as the LBO in which two optical axes exist, the n_{eff} is dependent on the refractive index, θ , and φ . θ is the angle between the propagation direction and the crystal's z axis, meanwhile, φ is the angle of rotation of the propagation direction in the XY -plane. The tuning of these parameters will determine the efficiency of the phase-matching condition. n_{eff} is defined as:

$$\frac{1}{n_{\text{eff}}^2} = \frac{\sin^2 \theta \cos^2 \varphi}{n_x^2} + \frac{\sin^2 \theta \sin^2 \varphi}{n_y^2} + \frac{\cos^2 \theta}{n_z^2} \quad (4.5)$$

The approach taken to solve this optimization problem was using a python script that easily tackled it. After running the program, from 4.5 the angular values that minimized the difference between $n_{\text{eff}}(\omega)$ and $n_{\text{eff}}(2\omega)$ was $\theta=90^\circ$ and $\varphi=0^\circ$.

Damage Threshold. The Laser-Induced Damage Threshold (LIDT) determines the maximum energy per pulse and peak power the crystal can receive without permanently damaging it or drastically reducing its useful life. An LBO crystal has an exceptional tolerance because of a low optical absorption and high optical homogeneity. These characteristics make it perfectly suited and indispensable to high-power lasers and ultra-short pulses.

The LIDT depends on the functioning wavelength, pulse duration and Frequency repetition rate. *Eskma* provides a base value of LIDT for 10 ns pulses at 1064 nm with a frequency rate of 10 Hz, specified as 5 J/cm² or >500 MW/cm² [29]. Adjusting these values is crucial to obtain a reliable measurement of the LBO's damage threshold

Wavelength and LIDT generally show a directly proportional relationship; nevertheless, the difference between 1064 nm and 1047 nm is so small that the induced shift can be neglected. LIDT scales temporarily with the square root of the pulse duration, subsequently the relationship is defined as:

$$LIDT_{\text{ps}} \approx LIDT_{\text{ns}} \cdot \sqrt{\frac{\tau_{\text{ps}}}{\tau_{\text{ns}}}} \quad (4.8)$$

Obtaining the necessary data from Table 3, the LIDT comes out to be 0.15 J/cm² or 16.7 GW/cm². It is observed that the crystal becomes more resistant to power peaks but less tolerant towards energy bursts. As expected, the LIDT of the LBO is orders of magnitude above the peak power and energy per pulse values of the laser configuration. This indicates that the LBO crystal's capabilities will not be hindered by the laser's characteristics, unlike what would happen in other nonlinear crystals.

Even with the robustness presented, at high frequencies like 2 kHz, cumulative damages due to heat retention become significant. Temperature is a variable that must be controlled to avoid the generation of heat gradients that deteriorate phase-matching.

Nonlinear coefficients. The second-order effective coefficients are $d_{31} = 1.05$ pm/Vd and $d_{32} = -0.98$ pm/Vd given by the manufacturer's specifications. The conversion efficiency is conditional on the nonlinear coefficient, as a higher value will improve the SHG performance. In the XY -plane, the effective coefficient is given by:

$$d_{\text{eff}} = d_{32} \cos \varphi \quad (4.7)$$

For the chosen angular orientation of the crystal, d_{eff} is maximized. In an LBO crystal, the nonlinear coefficient is comparably smaller than in BBO or KTP crystals; nevertheless, this crystal was chosen for its previously examined advantages in low walk-off, angular stability, and damage resistance. The compensation makes it an ideal crystal for a high-powered laser system like the one studied, as the intensity pumped into the LBO will compensate for the nonlinear coefficient factor. The equilibrium between performance and robustness the LBO crystal displayed was the reason for its purchase. Demanding applications such as SHG are feasible as a result of the optimal configuration and intrinsic properties of the nonlinear material.

In conclusion, while other crystals like BBO offer higher nonlinear coefficients, or PPLN allows for quasi-phase matching (see Table 2), the LBO crystal was strategically chosen as the optimal compromise for the specific parameters of the developed laser system. The high peak power (~ 13.33 MW) and ultrashort pulses (~ 9 ps) generated, make the system highly susceptible to nonlinear effects beyond SHG, such as self-focusing, and place high demands on the material's damage threshold. The LBO crystal's exceptionally high damage threshold (calculated to be ~ 16.7 GW/cm²) provides a crucial safety margin against the high peak intensity of the beam. In contrast, a crystal like PPLN, despite its very high efficiency, has a much lower damage threshold and would be at significant risk of being damaged. Furthermore, the LBO's low angular walk-off is essential for maintaining good beam quality, a critical factor for the subsequent precise focusing required for LPG inscription. Therefore, the LBO serves as the optimal choice to balance efficiency with the robustness required for high-power picosecond applications.

4.2 SHG Configuration

Regardless of the optimisation of the configurations and properties of the crystal, SHG requires a careful and precise alignment to maximize conversion and perform efficiently. To subside the heat preoccupation that arose when studying the LDT parameter, the crystal was mounted inside a Heatpoint Oven (*Eksma Optics*) [31]. The device serves as a compact oven that actively regulates the temperature of the LBO, ensuring the 2 kHz frequency will not cause the formation of temperature gradients. Moreover, by maintaining the crystal at a stable 26° (room temperature), the phase-matching condition is correctly preserved.

Having characterised previously the beam's waist at 20 cm from the laser's output, the crystal was purposely positioned there. The narrow diameter of 776 μm allows the beam power density to be maximized. Doing so concentrates the beam more within the nonlinear medium, providing greater conversion efficiency.

The initial alignment was focused on accomplishing a collinear incidence between the optical axis of the laser and the LBO's axis. If the two are perfectly aligned without any angular deviation, the second harmonic generation will proceed under optimal conditions. To correctly monitor the SHG process, a low-pass filter and the A-10-D12-HP thermal sensor were employed. The low-pass filter reflects beams with a wavelength larger than 750 nm, isolating the second harmonic beam. Notably, the filter must be tilted so the fundamental beam does not reflect towards the crystal and laser, as it can damage the optical components. Additionally, the sensor quantifies the average power of the second harmonic obtained, as a means of finely adjusting the alignment.

Three different crystal configurations were explored. Firstly, the oven containing the crystal was mounted in a cage plate from *Thorlabs*, specifically model CP02/M [32]. In this configuration, the crystal remained fixed without the possibility of any angular adjustment. A faint green point was observed under dark conditions, showcasing the low intensity achieved during the SHG process. This simple disposition was inefficient, as it provided a low conversion efficiency due to a suboptimal coupling between the fundamental beam and the optical axis of the crystal.

In the second configuration, a high-precision rotation mount was incorporated, which was the PRM1 from *Thorlabs* [33]. This mount allows for 360° rotation that can adjust the orientation angle of the crystal along one rotation axis. After assembly, a considerable change in the second harmonic intensity was appreciated, as the mount introduced the ability to sweep to determine the optimal angle. The introduction of a controlled angular degree of freedom resulted in the refinement of the phase-matching condition.

Lastly, a kinematic prism mount was integrated into the system. The KM200PM from *Thorlabs* was coupled with the PRM1 rotation mount to provide additional control over the crystal's inclination over two orthogonal axes [34]. With this biaxial control, small deviations of the optical axis of the laser beam were compensated. The resulting robust, reproducible, and highly efficient second harmonic generation and angular coupling allowed the crystal to operate under near-optimal phase-matching conditions. This resulted in the highest stability and beam intensity at 523.5 nm (SHG).

4.3 Characterization of SHG

Once SHG is achieved, the generated beam must have its efficiency, stability, and spatial quality evaluated. Compiling these characteristics concludes the possible applications for which the laser is suitable. The characterization of the second harmonic generation is detailed below

4.3.1 Conversion Efficiency

The efficiency of the SHG process is defined as the extracted power of the second harmonic beam over the power generated by the laser system. It is a way to determine how much of the incident power is converted into the second harmonic wavelength (523.5nm). The equation is described as:

$$\eta = \frac{P_{2\omega}}{P_{\omega}} \quad (4.8)$$

The alignment configuration was utilized to measure the optical power of the second harmonic. The low-pass filter ensured only the 523.5 beam was transmitted, and the sensor A-10-D12-HP was configured with the most suitable parameters for this measurement. A value of 118 mW was measured after all the optimisations detailed in the 4.2 subsection. From equation 4.8, the conversion efficiency is calculated to be $\eta \approx 49\%$. This value showcases that the SHG configurations are well defined, as an efficiency in the range of 40-50% is considered satisfactory when talking about nonlinear conversion processes. For a single-pass LBO configuration under similar pumping conditions, efficiency values typically range from 30% to 50% [20, 21].

4.3.2 Generated Wavelength

A spectrometer (CS100 from Thorlabs) was employed to verify if the emission peak of the second harmonic corresponds to the expected wavelength of 523.5 nm [35]. This step, although simple, is crucial to confirm that the SHG process occurs efficiently and free of spurious constraints (signals that do not correspond to the SHG process). In Figure 17, the spectrum is observed, and the emission peak corresponds, as anticipated, to half of the fundamental wavelength.

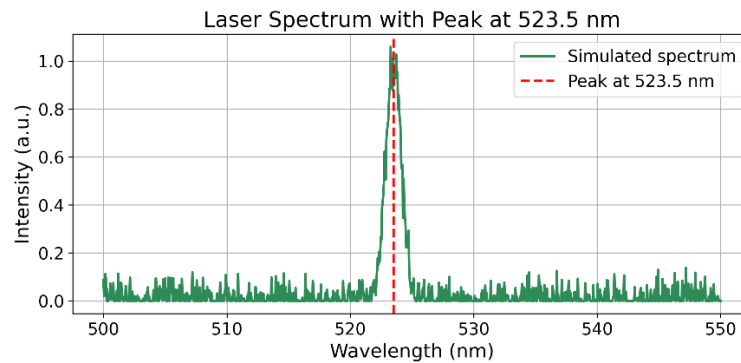


Figure 17. Spectrum of the second harmonic generation (SHG) output. The peak is centered at 523.5 nm.

4.3.3 Beam Profile

To correctly guarantee proper spatial coupling and optical alignment during the second harmonic generation, the beam profile must maintain its Gaussian nature. Qualitatively, this was verified by projecting the isolated 523.5 nm beam onto a graph paper. A circular pattern with maximum intensity in the centre and a symmetric and progressive decay towards the edges was observed. This behaviour is typical of Gaussian pulses, although the BeamMaster software was once again used for a more accurate evaluation.

The BeamMaster software provided the characteristic parameters of the beam from which the Gaussian correlation was still near 90%, albeit slightly smaller. This value confirms the previous suppositions that the second harmonic beam maintains a Gaussian profile. Moreover, the beam diameter is characterized at 20 cm, as shown in Table 7.

<i>Profile</i>	<i>Intensity (%)</i>	<i>Measured Diameter (μm)</i>	<i>Adjusted Diameter (μm)</i>
<i>V (Horizontal)</i>	80%	200.2	227.6
<i>V (Horizontal)</i>	50%	381.6	391.5
<i>V (Horizontal)</i>	13.5%	732.4	672.1
<i>W (Vertical)</i>	80%	145.9	160.9
<i>W (Vertical)</i>	50%	288.1	289.4
<i>W (Vertical)</i>	13.5%	525.6	489.7

Table 7. Characterization of the second harmonic beam diameter at a distance of 20 cm.

The beam diameter is proportional to the square root of the wavelength. Therefore, using a simple relationship of variables, the second harmonic beam can be estimated to be 30% smaller than the fundamental beam diameter. The experimental data obtained corroborate this relation with minimal percentual difference (3-4%), confirm that the beam maintains a Gaussian profile, and demonstrate that the system does not alter the beam size.

At 13.5% intensity, the beam diameter is substantially larger than the diameter of a fibre nucleus ($\sim 9 \mu\text{m}$). Consequently, to enable the inscription of an LPG, the beam must be both vertically and horizontally compressed.

4.3.4 Angular dependency

By fine-tuning the PRM1 rotation mount, a sweep is achieved over the angles of incidence of the fundamental beam. This represents the angle at which conversion is maximized. Figure 18 shows that the maximum power is at 90° . This coincides with the $\theta=90^\circ$ crystallographic axis cut of the crystal, which was specified during its selection. By fulfilling this condition, the beam travels perpendicular to the optical axis, and it is possible to take advantage of the non-critical phase coincidence configuration.

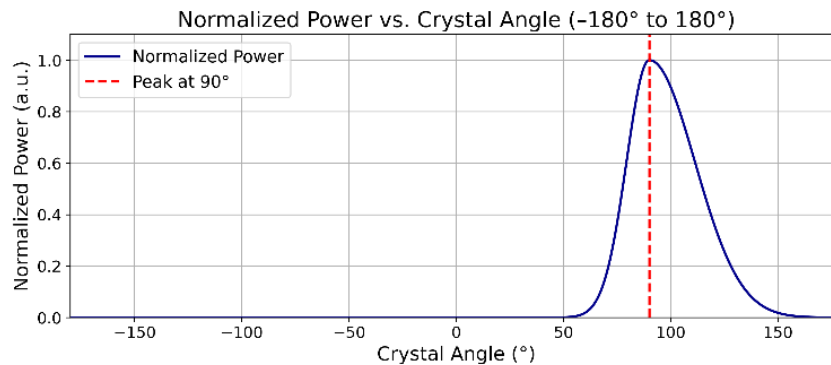


Figure 18. Normalized power of the second harmonic generated as a function of the crystal rotation angle.

Chapter 5. LPG Inscription and Sensing Capabilities

The purpose behind characterizing the laser system and achieving second-harmonic generation was to enable the inscription of a long-period grating onto a photosensitive optical fibre. The preceding experimental steps were essential for determining the suitability of the laser for this specific application. Through this process, both the operational capabilities and inherent limitations of the system were clearly established, hence providing a thorough framework for its use in precision photonic applications such as fibre grating inscription.

A more meticulous optimisation of the generated second harmonic was required to inscribe gratings onto the fibre. The optical system was therefore adapted to focus the second harmonic beam onto the fibre core with high spatial resolution. Given that the beam's diameter is approximately in the order of hundreds of microns (see table 7), and the diameter of the core of a single-mode fibre stands around 9 μm a substantial beam compression is necessary. To make this possible, an optical system to compress the beam in both spatial directions was introduced into the configuration.

By compressing the laser beam to a spot size comparable to the fibre core, the energy density (power per unit area) is dramatically increased. This high-intensity region induces a localized and controlled modification of the refractive index in the core through nonlinear optical effects. The precision of the process depends critically on the beam's geometry, as smaller spots generate more confined index changes that will lead to better-defined grating.

5.1 Configuration

5.1.1 Fibre Adjustment

The optical fibre, positioned onto a mount with specific optical fibre clamping and maintained straight, was placed onto an LS-180 motorized linear stage from *Physik Instrumente* (PI) [36]. The platform, equipped with a BLDC motor, enables submicrometric resolutions with a maximum displacement of 180 mm and a typical repeatability of $\pm 0.2 \mu\text{m}$. The ability to perform precise and programmed movements during laser exposition provides ideal conditions to inscribe periodic structures within the optical fibre. The linear stage ensures fine-tuned control over the periodicity of the inscribed grating.

Unfortunately, the incorporation of said platform led to a considerable difference between the working planes of the fibre and the laser. The fibre mount was elevated approximately 11 cm with respect to the original plane of the optical system, which required a readjustment. The elevation of the laser and the LBO crystal completely disrupted the

optical alignment previously performed and forced to, once again, optimize the system and the SHG.

5.1.2 Beam alignment and compression

After the setbacks were dealt with, the laser system was properly aligned with the fibre. As a means of visually observing the alignment, a small screen was positioned behind the fibre. The superposition of the beam and fibre was observed in the screen as the projected shadow of the fibre passed through the centre of the beam profile. Notably, with this disposition, it was visually verified that the beam was considerably larger than the optical fibre, which would prevent accurate inscription.

Consequently, the beam was compressed with a plano-convex lens to concentrate the optical energy into a reduced volume. The spherical lens with a focal point of 300 mm was positioned at its focal distance from the fibre plane to compress the beam in its horizontal axis. The horizontal component was addressed first, although its angular divergence is lower, this axis presents a considerable larger diameter at short propagation distances (as shown in Table 4 and Table 7), so its compression was prioritized to equalize the beam's dimensions.

After the lens was correctly mounted, adjusted, and aligned with the beam path, the spot's dimensions were reduced, and vertical lines began to appear on the rear screen. This phenomenon is attributed to the diffraction caused by the partial coherent obstruction the fibre does towards the focalised beam. When the beam approaches the size of the fibre nucleus, diffraction effects become prominent and these visible interference fringes are produced. Diffraction serves as a visual indicator to optimize the distance between the lens and the fibre. Approaching the focal point will reduce the spot, therefore intensifying the observable diffraction effects.

In order to observe this, the screen is positioned at the Fourier plane of the optical system. The Fourier plane represents the plane where the intensity distribution corresponds to the spatial Fourier transform of the beam modified by the fibre.

To complete the bidimensional compression of the beam, a second lens was introduced into the configuration, this time a plano-convex cylindrical lens with a 25 mm focal distance. The remaining axis of the beam was properly focused by orienting it orthogonally with respect to the previous lens. Upon aligning all the optical elements, an approximately circular spot with comparable dimensions to the fibre nucleus was observed. Under this configuration, a more defined diffraction pattern appeared on the screen, signalling the extreme focus achieved.

In particular, it is fundamental for the beam to remain centred with respect to the optical axis of both lenses. Any angular deviation or laser beam displacement will compromise the effectiveness of the inscription process or prevent it completely.

Furthermore, an electrical element was inserted between the nonlinear medium (LBO crystal) and the lens arrangement. This component is a shuttering screen, providing precise control over the beam's transmission to the fibre. Connected to the controller that regulates the motorized linear stage, a high-level signal output will open the shutter, while a low-level signal output will block the beam. The shutter enables the formation of periodic structures along the fibre by spatially and temporally regulating laser exposure. Figure 19 displays the laser system in its final aligned configuration.

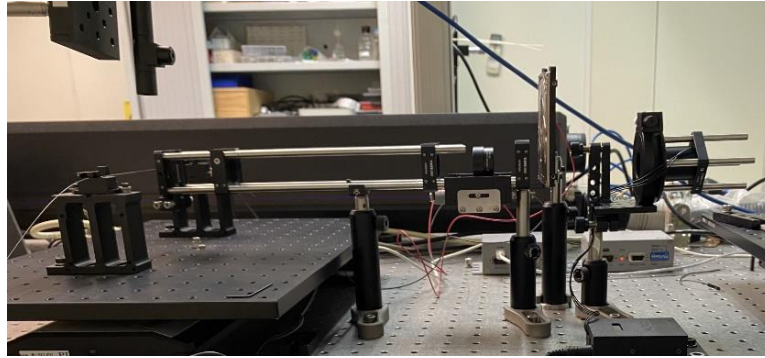


Figure 19. Laser system for fibre inscription.

An attempt was made to inscribe a long-period grating using this configuration, although unsuccessful. Therefore, a telecentric lens camera was incorporated to directly observe the interaction between the laser beam and the fibre. The camera was positioned above the fibre, and the focus length was adjusted on the beam's incidence area on the core. The resulting image is shown in Figure 20. It can be seen that the optical configuration employed produces a relatively small beam, although not compressed enough to achieve the energy density necessary to induce an appreciable refractive index change in the fibre.

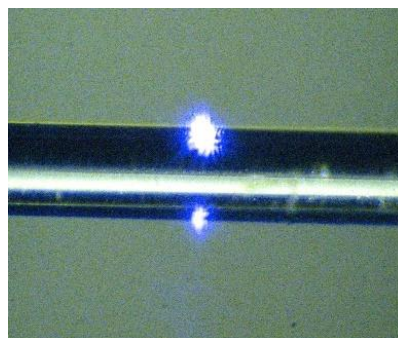


Figure 20. Incidence of the collimated beam on the coated optical fibre.

5.1.3 Reconfiguration of the system

The experimental system was re-evaluated in response to the suboptimal outcomes of the LPG inscription process. It was concluded that the spatial compression of the beam did not achieve sufficient localized intensity or resolution to produce a permanent refractive

index change in the fibre. After careful consideration, another strategy was chosen, opting for the implementation of a more precise focusing optical element.

Specifically, the Mitutoyo M Plan APO NIR HR 50x lens was incorporated into the configuration [37]. Although marketed for applications in the near infrared (NIR), its operation wavelength ranges from 480 to 1800 nm, therefore fitting perfectly with this system that functions at a wavelength of 523.5 nm. The lens offers low aberration and an extremely high power density in its focal point (~ 4 mm). This component was chosen to replace the previous assembly due to its ability to focus beams at 50x magnification. This magnification will greatly reduce the spot, thus confining the energy into a tighter space to perform sharp gratings.

The lens was mounted on the same previous structure, eliminating the previous focusing lenses, but preserving the general alignment of the system. This allowed for a seamless transition that did not require a new complete beam alignment. A few adjustments were made to perfectly strike on the centre of the lens, to avoid any potential distortion that could negatively impact the performance and magnification capabilities of the lens. The decision to retain the pre-established configuration allowed for a more efficient use of time and resources, as it maintained the collinearity and centring of the beam with respect to the fibre setup. Figure 21 displays the new configuration.

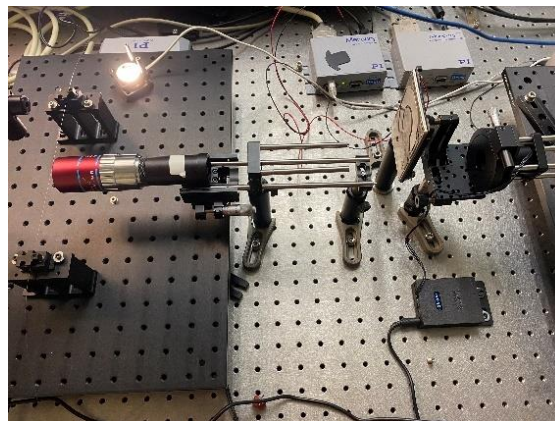


Figure 21. Laser system with magnification lens for fibre inscription.

Unsurprisingly, this alternative configuration turned out to be more efficient than the previous system. Figure 22 exhibits the spot obtained by impinging on a bare fibre. It is clearly observed that the spot dimensions are on the order of the fibre core and are significantly smaller than the spot obtained with the conventional lens configuration displayed in Figure 20. The provided well-defined and narrowed beam substantially increased the peak intensity at the focal region. Achieving a sufficiently high energy density in a small volume is critical to generate nonlinear modifications of the refractive index at the submicron scale, necessary for the inscription of LPGs.

Unfortunately, due to the fixed plane of incidence on the fibre and its mounting, which does not allow for rotation, it proved challenging to achieve the precise adjustment required to focus all the beam's energy on the fibre. Under the described conditions, the entire fibre dimension cannot be appreciated, meaning it is not possible to accurately

assess the exact point of incidence and its effects. This can negatively affect the LPGs' resolution, since incomplete energy delivery reduces the efficiency of the inscription process.

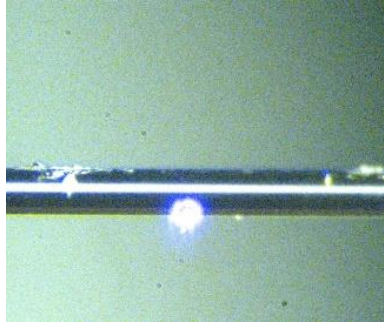


Figure 22. Incidence of the collimated beam on the fibre nucleus.

5.2 Inscription Process

The process begins with confirming that the beam equally impinges on the fibre along all its positions. Any minor beam misadjustment will cause an uneven exposure to the fibre, negatively impacting periodic structure formation. The fibre must be cleanly and accurately incident on both fibre ends to verify adequate alignment.

Due to practical requirements in the laboratory, gratings were designed with a $365\text{ }\mu\text{m}$ periodicity, which corresponds to a resonant wavelength of approximately 1530 nm according to equation 2.13. The motorized linear stage and shutter, run by a controller, regulated the punctual irradiation process. The inscription was performed in a point-by-point method, in which the linear platform moved in a controlled manner to define the successive positions of the refractive index modulation induced by the laser beam. A macro was programmed using the native PI software and its built-in code.

The process began by moving the stage to position the laser focus over the initial writing region. Thereafter, a high-level signal activated the shutter allowing for the radiation to be incident on the fibre during a distance of $\frac{\Lambda}{2} - W$, where Λ is the grating period and W the effective beam width. The speed was adjusted to be 0.01 mm/s in order to provide a slow and methodical localized exposition along the exposed fibre, potent enough to generate a permanent change to the glass' refractive index.

After the initial exposition, the shutter is blocked, and the stage is displaced a distance of $\frac{\Lambda}{2} + W$. This generates the corresponding separation between the attacked regions, maintaining the desired periodicity along the longitudinal axis of the fibre. The first section of the grating is now formed, and this exposure is looped until the desired attenuation or length of the LPG is achieved.

If the beam width is not taken into consideration, the grating period will vary, and therefore, the desired Bragg wavelength will not be achieved. From the images taken of the spot, such as Figure 22, the collimated beam width at the focus point of the system is estimated to be $\sim 20\text{ }\mu\text{m}$. Supposing that the width is irrelevant, the resulting grating period will be around $385\text{ }\mu\text{m}$, resulting in a resonance wavelength of 1613 nm (using equation

2.13). That is the reason behind including the beam width during the inscription process, as the better it is parametrized, the more accurate results will be achieved. Figure 23 shows this effect.

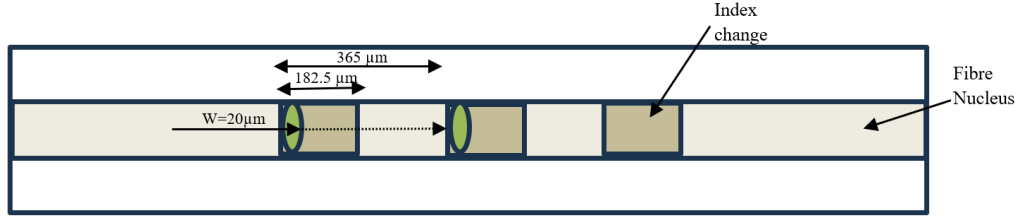


Figure 23. Diagram of the LPG inscription process.

5.3 Results

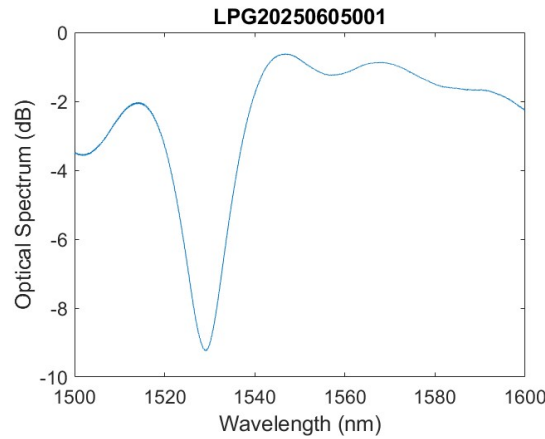


Figure 24. Spectral response of a LPG inscribed in single-mode fibre using a picosecond laser system with a grating period of 365 µm and a total length of 7 cm.

Figure 24 showcases the spectral response of the LPG inscribed on a single-mode photosensitive fibre, through the previously defined protocol. The irradiation of the picosecond laser pulses at 523.5 nm was performed with a periodicity of 365 µm, reaching its maximum transition attenuation for 200 cycles. Consequently, the LPG length resulted in approximately 7 cm.

5.3.1 Spectral Analysis

The observed transmission spectrum displays a resonant wavelength centred around 1530 nm with a maximum attenuation of **~9 dB** (~12.5% transmission of incident power). The experimentally observed spectral attenuation validates the laser system's ability to deliver adequate power density for inducing periodic and sufficiently strong refractive index changes in the fibre. The presence of a clear resonance also supports that efficient SHG is being achieved, as the phase-matching and nonlinear conversion conditions are met. Furthermore, the detection of a resonant wavelength at the theoretical value indicates a successful configuration and optimization of the laser's alignment and beam compression, as well as the implementation of a precise inscription protocol.

Nevertheless, the accomplished attenuation is significantly inferior to other, more mature or energetically intense inscription laser systems. In direct comparison, a femtosecond laser consistently achieves attenuations superior to 20 dB, resulting in $< 1\%$ transmission [14]. The notable difference in the coupling efficiency is attributed to diverse factors related mainly to the energy density per pulse. The picosecond laser system, although potent enough to induce an appreciable periodic refractive index change in the fibre, does not compare to the peak power per area achieved by the femtosecond laser. Other relevant factors influencing this process include the optical setup itself, as a suboptimal beam incidence on the fibre may result in incomplete energy delivery and a lower-than-expected refractive index change. The astigmatism and ellipticity measured in Chapter 3.4.2 likely contributed to the difficulty in achieving a perfectly circular and symmetric focal spot, which is critical to be fully incident on the fibre. Additionally, the alignment of the SHG stage plays a crucial role in ensuring sufficient energy reaches the inscription zone.

5.3.2 *Potential in optical sensing*

The resonant wavelength is located within the C band ($\sim 1530\text{--}1565$ nm) meaning the LPG is suitable for integration into standard optical interrogation systems. The observed spectral form (from Figure 24) shows an absence of unwanted background noise, which indicates good longitudinal uniformity in the inscription. Having a clean spectral form demonstrates that it is a highly stable system.

Despite the attenuation limitations, the inscription quality obtained with the picosecond laser demonstrates adequate control over the LPG creation process. Despite the moderate attenuation, which reduces both sensitivity and spectral resolution, the sensor remains capable of detecting minor variations in the surrounding environment, highlighting its relevance in practical sensing applications. Not only that, but the customization of the resonant wavelength by varying the grating period or the total length of the modulation enables a wide range of applications.

In conclusion, the picosecond laser inscription method with SHG, although less potent than others, offers a greater experimental simplicity and exceptional mechanical robustness (inscription methods using UV wavelengths can more easily damage the internal glass structure of the fibre [14]). In addition, improving the energy concentration or the design of the inscription configuration could lead to better results. These characteristics make it attractive for applications where the structural integrity of the fibre is critical, such as sensors positioned in harsh environments or subjected to bending.

Chapter 6. Conclusions and Future Projects

Conclusions

This bachelor's thesis sets out to achieve the objective of designing, implementing, and characterizing a picosecond pulsed laser system, including the generation of its second harmonic, with the purpose of evaluating its viability in sensor applications by way of the inscription of a long-period grating (LPG) in an optical fibre. Through a rigorous and meticulous multi-stage experimental procedure, the functionality and versatility of the developed laser system has been successfully demonstrated. Significantly, all the proposed specific objectives have been clearly and unambiguously met.

The project's first phase was centred on characterizing the 1047 nm pulsed laser. The exploration of its characteristics and components served as the basis for the rest of the project. After a thorough alignment and optimization process, the experimental results demonstrated that the system was a robust and high-performance system. Ultrashort pulses with an estimated duration of 9 ps and a remarkable peak power of 13.33 MW at a repetition rate of 2 kHz were achieved. These parameters not only validated the correct operation of the Q-switching configuration but also established a more than sufficient energy base for addressing nonlinear optical processes.

Subsequently, an LBO nonlinear crystal was investigated, selected, and successfully integrated into the laser system, enabling the occurrence of second harmonic generation (SHG). The use of high-precision mounts in the alignment and angular optimization stage facilitated and culminated in the generation of a stable beam at 523.5 nm. The most noteworthy aspect accomplished during the SHG was the excellent power conversion efficiency obtained. An efficiency value of 49% demonstrates precise control over the phase coupling process and effective management of the high peak power of the fundamental laser.

Finally, the laser system was employed to inscribe an LPG, representing the challenge of integrating all the previous stages and properly evaluating the capabilities and potential applications of the system. After initial struggles, a high magnification objective (50x) was implemented to focus the beam to the micrometre scale of the fibre core, demonstrating the adaptability and problem-solving capacity of the assembly. With this set-up, a successful fabrication of an LPG with a length of 7 cm and a resonance attenuation of approximately 9 dB at the theoretical wavelength of 1530 nm, within the telecommunications C band, was achieved.

Even if the obtained attenuation lacks in comparison with femtosecond laser systems due to energy constraints, the obtained spectrum conclusively validates the viability and versatility of the picosecond system for microfabrication in optical fibre. Beyond this, the picosecond laser system has also been consolidated as a complete and versatile experimental platform. Having the capability of operating in two distinct wavelengths (1047 and 523.5 nm) and an accurate control over pulse modulation makes it an adaptable

tool for future research in the field of photonic sensors, materials processing and nonlinear optics.

Beyond the technical achievements, the developed laser system holds significant potential to contribute to global sustainability targets. The project heavily aligns with the United Nations' Sustainable Development Goals (SDGs), particularly addressing SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities). The creation of an innovative technological platform for advanced manufacturing of optical sensors enables the structural health monitoring of critical infrastructure (bridges, pipelines, etc.). This, in turn, enhances their safety, resilience, and operational lifespan, which are core targets of SDG 9. This impact further extends to SDG 11, as optical sensors are non-invasive, non-destructive, and more energetically efficient than conventional alternatives. Deploying these sensors to ensure the integrity of urban assets will contribute to the creation of healthier and more sustainable urban environments. These applications exemplify how advanced photonics, and optical physics can be utilized to address real-world engineering challenges, highlighting the role engineering physics plays in sustainable development.

Altogether, the developed findings fully validate the effectiveness of the experimental system as a whole, ranging from the generation of ultrashort pulses to their practical application in photonics. Having developed and characterized a versatile system capable of manufacturing optical sensors, a solid foundation has been laid for future research and technological development projects.

Future Projects

The experiment has been successful in implementing and characterizing this picosecond laser system. However, obvious limitations prevent the development of a state-of-the-art system. Through certain proposals detailed below, the aim is to open the door to numerous lines of research and expand the field of applications. The following projects represent meaningful advancements that will open new avenues for research and innovation within the scientific and technological landscape.

Even though the laser system has inscribed a functional LPG, its performance is inherently limited by the lack of power. To unlock higher levels of functionality and performance, the following redesigns of the optical cavity are proposed.

- One option would be the substitution of the current pumping diode in favour of a higher-power alternative. An increase in the pumping power contributes to a greater accumulation of energy in the active medium (Yb:YAG). This results in output pulses with greater energy and, consequently, higher peak power.
- Another possible alternative, although experimentally more complicated, would result in a revolutionary improvement for the characteristics of the system. Replacing the Acousto-Optical Modulator (Q-switch) with a Mode-Locking system would force phase coherence between the longitudinal modes of the laser. This would produce periodic constructive interference that surpass the picosecond barrier to reach the femtosecond regime. The drastic reduction of the pulse

duration would, for the same energy, elevate the peak power achieved. Combining both enhancements, would lead to a highly precise and efficient micromanufacturing system.

Implementing either proposal would require a new design and characterization of the fundamental laser at 1047nm, being a long-term project.

On the other hand, the lateral incidence configuration showed some alignment challenges that could potentially lead to a suboptimal energy deposition. A reconfiguration of the system could effectively tackle this problem. A top-down inscription method is proposed, in which the laser beam would be directed perpendicularly onto the fibre. With this configuration, a critical alignment dimension is effectively eliminated, facilitating the inscription process. However, it would also involve re-raising the entire laser system.

The main advantage of the top-down inscription approach lies in its ability to leverage index-modified coatings on the fibre to maximize energy efficiency [38]. By applying a coating with a refractive index higher than that of the original cladding, the waveguide locally disrupts and scatters light at the interface. As a result, the interaction region becomes visible, and the area of greatest intensity will be visible on the camera to ascertain the quality of the achieved coupling. Efficient energy deposition into the fibre core would induce a stronger and more sharply defined refractive index modulation, enabling the fabrication of long-period gratings (LPGs) with attenuation levels significantly higher than the 9 dB obtained.

This method also unlocks new application possibilities for the laser system. By coating the fibre with specific polymers, LPGs can be designed to detect specific chemical compounds [39]. The application of functional coatings on the fibre is facilitated, making it possible to deposit specific polymers or reagents on the fibre. Thereafter, chemical or biological sensors could be developed by using the laser to modify the coating locally or to inscribe the grating through it.

Additionally, other lines of research that are not based on modifying the existing laser system would be to expand the type of manufactured devices and the materials used. For example, ultra-short pulses have the ability to process non-photosensitive materials [7]. Future projects could explore the possibility of inscribing in non-standard fibres, such as multicore fibres or special glass fibres, the objective being the development of sensors for extreme environments where standard fibres fail. Simultaneously, the investigation into the fabrication of more complex structures beyond uniform LPGs, such as tilted FBGs, would offer distinct sensitivities and functionalities in previously unexplored areas of application.

These future lines of investigation, which build directly on this project's achievements, highlight the vast potential of the system. Therefore, showing that the current and future goal is to develop a first-class photonics research and manufacturing platform capable of producing high-performance sensors and exploring the limits of laser materials processing.

Bibliography

- [1] M. H. Niemz, *Laser-Tissue Interactions: Fundamentals and Applications*, 3rd ed. Berlin, Heidelberg: Springer-Verlag, 2007.
- [2] G. W. Yang, “Laser ablation in liquids: Applications in the synthesis of nanocrystals,” *Progress in Materials Science*, vol. 52, no. 4, pp. 648–698, Apr. 2007.
- [3] K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, “Writing waveguides in glass with a femtosecond laser,” *Optics Letters*, vol. 21, no. 21, p. 1729, Nov. 1996.
- [4] Y. Ran, L. Jin, Y. L. Tan, S. K. Khijwania, and B. O. Guan, “Femtosecond laser inscribed high-temperature sensor based on a long-period fiber grating,” *Journal of Lightwave Technology*, vol. 32, no. 13, pp. 2335–2339, Jul. 2014.
- [5] Y. Lai, K. Zhou, L. Zhang, and I. Bennion, “In-fiber Mach–Zehnder interferometer for strain and temperature sensing based on a femtosecond-laser-micromachined single-mode fiber,” *IEEE Photonics Technology Letters*, vol. 18, no. 1-4, pp. 596–598, Feb. 2006.
- [6] T. Geernaert et al., “Femtosecond laser-induced fiber Bragg gratings in non-sensitized polyimide-coated single-mode fiber,” *Optics Letters*, vol. 35, no. 10, p. 1647, May 2010.
- [7] R. R. Gattass and E. Mazur, “Femtosecond laser micromachining in transparent materials,” *Nature Photonics*, vol. 2, no. 4, pp. 219–225, Apr. 2008.
- [8] B. Lee, “Review of the present status of optical fiber sensors,” *Optical Fiber Technology*, vol. 9, no. 2, pp. 57–79, Apr. 2003.
- [9] J. Hecht, *Understanding Lasers: An Entry-Level Guide*, 3rd ed. Hoboken, NJ, USA: Wiley-IEEE Press, 2008.
- [10] W. Koechner, *Solid-State Laser Engineering*, 6th ed. New York, NY, USA: Springer, 2006.
- [11] A. Marcinkevičius, S. Juodkazis, M. Watanabe, M. Miwa, S. Matsuo, H. Misawa, and J. Nishii, “Femtosecond laser-assisted three-dimensional microfabrication in silica,” *Optics Letters*, vol. 26, no. 5, p. 277, Mar. 2001.
- [12] G. D. VanWiggeren, T. K. Gaylord, D. D. Davis, E. Anemogiannis, B. D. Garrett, M. I. Braiwish, and E. N. Glytsis, “Carbon dioxide laser-induced long-period fiber gratings: fabrication and theoretical analysis,” *Journal of Lightwave Technology*, vol. 18, no. 12, pp. 1988–1998, Dec. 2000.
- [13] B. N. Chichkov, C. Momma, S. Nolte, F. von Alvensleben, and A. Tünnermann, “Femtosecond, picosecond and nanosecond laser ablation of solids,” *Applied Physics A*, vol. 63, no. 2, pp. 109–115, Aug. 1996.
- [14] S. I. Mihailov, “Fiber Bragg grating sensors for harsh environments,” *Sensors*, vol. 12, no. 2, pp. 1898–1918, Feb. 2012.

- [15] B. S. Yilbas, “Repetition rate in pulsed laser treatment of materials and its influence on the resulting surface quality,” *Optics and Lasers in Engineering*, vol. 45, no. 7, pp. 753–761, Jul. 2007.
- [16] A. Othonos and K. Kalli, *Fiber Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensing*. Boston, MA: Artech House, 1999.
- [17] A. E. Siegman, *Lasers*. Sausalito, CA, USA: University Science Books, 1986.
- [18] O. Svelto, *Principles of Lasers*, 5th ed. New York, NY, USA: Springer, 2010.
- [19] W. W. Rigrod, “Saturation effects in high-gain lasers,” *Journal of Applied Physics*, vol. 36, no. 8, pp. 2487–2490, Aug. 1965.
- [20] R. W. Boyd, *Nonlinear Optics*, 4th ed. London, UK: Academic Press, 2020.
- [21] V. G. Dmitriev, G. G. Gurzadyan, and D. N. Nikogosyan, *Handbook of Nonlinear Optical Crystals*, 3rd ed. Berlin, Heidelberg: Springer-Verlag, 1999.
- [22] Crytur. (2023). *Yb:YAG - Ytterbium doped YAG single crystal* [Online]. Available: <https://www.crytur.com/materials/ybyag/>
- [23] D. C. Brown, “Heat, stress, and birefringence in solid-state lasers,” *IEEE Journal of Quantum Electronics*, vol. 34, no. 12, pp. 2379–2392, Dec. 1998.
- [24] Gooch & Housego. (2023). *Acousto-Optic Q-Switch I-M080-2C10G-4-AM3 Datasheet* [Online]. Available via Gooch & Housego product inquiry.
- [25] LaserPoint. (2023). *A-10-D12-HP Thermal Sensor Head Datasheet* [Online]. Available: <https://www.laserpoint.it/>
- [26] Thorlabs, Inc. (2023). *DET08CFC - 5 GHz InGaAs Biased Detector, 800-1700 nm, FC/PC* [Online]. Available: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=2910
- [27] Yokogawa Test & Measurement Corporation. (2023). *AQ6373B Optical Spectrum Analyzer* [Online]. Available: <https://tmi.yokogawa.com/solutions/products/optical-measuring-instruments/optical-spectrum-analyzer/aq6373b-optical-spectrum-analyzer/>
- [28] Coherent, Inc. (2023). *BeamMaster Beam Profiler System* [Online]. Available: <https://www.coherent.com/measurement-control/laser-beam-diagnostics/products/beam-profilers-power-energy-meters/beam-profilers>
- [29] International Electrotechnical Commission. (2014). *Safety of laser products – Part 1: Equipment classification and requirements* (Standard No. IEC 60825-1:2014). Geneva, Switzerland: IEC.
- [30] EKSMA Optics. (2023). *LBO Crystals for SHG/THG/OPO* [Online]. Available: <https://www.eksmaoptics.com/nonlinear-crystals/lbo-crystals/>
- [31] EKSMA Optics. (2023). *Heatpoint Oven for Nonlinear Crystals model 350-60* [Online]. Available: <https://www.eksmaoptics.com/optical-components/crystal-ovens-and-controllers/>

- [32] Thorlabs, Inc. (2023). *CP02/M - 30 mm Cage Plate, Ø1" Optic Mount, SMI-Threaded* [Online]. Available: <https://www.thorlabs.com/>
- [33] Thorlabs, Inc. (2023). *PRM1 - Ø1" Manual Rotation Mount* [Online]. Available: <https://www.thorlabs.com/>
- [34] Thorlabs, Inc. (2023). *KM200PM - Ø2" Kinematic Prism Mount* [Online]. Available: <https://www.thorlabs.com/>
- [35] Thorlabs, Inc. (2023). *CCS100 - Compact Spectrometer, 350-700 nm* (Nota: Se asume un modelo similar, CS100 no parece ser un producto actual, CCS series es el equivalente). [Online]. Available: <https://www.thorlabs.com/>
- [36] Physik Instrumente (PI). (2023). *LS-180 Motorized Linear Stage Datasheet* [Online]. Available: <https://www.physikinstrumente.com/>
- [37] Mitutoyo Corporation. (2023). *M Plan APO NIR HR Series Objectives Datasheet* [Online]. Available: <https://www.mitutoyo.com/>
- [38] Cooper, M. L.; Lloyd, G. R.; James, S. W.; Stretton, I. R. G.; Nash, G. R. and Tatam, R. P. "Externally-induced long-period gratings in liquid crystal clad fibres," *Optics Express*, vol. 15, no. 8, pp. 4885-4892, April 2007.
- [39] James, S. W. and Tatam, R. P. "Optical fibre long-period grating sensors: characteristics and application," *Measurement Science and Technology*, vol. 14, no. 5, pp. R49–R61, 2003.