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MASTER THESIS

DESIGN AND CHARACTERIZATION OF A FEMTOSECOND GAIN-MANAGED
FIBER AMPLIFIER SEEDED BY A Yb:KYW BULK LASER OSCILLATOR

PROGETTAZIONE E CARATTERIZZAZIONE DI UN AMPLIFICATORE GAIN-
MANAGED IN FIBRA AL FEMTOSECONDO, INNIETTATO CON UN OSCILLATORE
LASER Yb:KYW A STATO SOLIDO

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Introduction

Ultrafast laser sources have become essential tools across a wide range of scientific and industrial applications, including precision material processing, nonlinear microscopy, spectroscopy, frequency metrology, and optical communications. In industrial manufacturing, femtosecond and picosecond pulses are now widely employed for both surface micro/nanostructuring and three-dimensional processing inside transparent materials, exploiting ultrashort pulse widths and extremely high peak intensities that have opened new avenues in materials processing for both fundamental research and practical, commercial applications [1].

The extremely short interaction time confines energy deposition to the focal volume before significant heat diffusion can occur, enabling clean, high-precision material removal or modification with minimal thermal damage to the surrounding region—a decisive advantage over longer-pulses in applications such as micro-drilling, surface texturing, and the fabrication of photonic and microelectronic devices. The pulse energy required to enable such applications is not easily achieved directly from a mode-locked oscillator, making optical amplification a fundamental step in the development of high-power ultrafast systems of interest for industrial applications.

Amplification of ultrashort pulses, especially in the femtosecond time domain, poses significant challenges for several reasons: firstly, to maintain the original pulse duration unaltered after amplification, an amplifier with a large enough gain bandwidth must be employed to avoid, or limit, the so-called gain-narrowing effect [2]. Secondly, a proper strategy to avoid nonlinear effects that can compromise the spectral (and temporal) quality of the pulse during amplification must be adopted. Finally, pulse peak power during amplification must be kept below the

optical damage threshold.

Conventional chirped-pulse amplification (CPA) [3] circumvents nonlinear pulse distortion by stretching the pulse in the time domain before amplification by a properly designed linear chirp added typically with diffraction gratings. In this way, the pulse peak power is reduced to a damage-safe level, and nonlinear effects are minimized. After the amplification, a grating pulse compressor restores, ideally, the original pulse duration by applying to the pulse a linear chirp of opposite sign. This concept can be applied at different pulse energy levels by adjusting the amount of pre-chirp, so it is intrinsically scalable. It can also be applied for both fiber-based and bulk amplifiers. However, some limitations still exist. Besides the intrinsic complexity and bulkiness of the CPA amplifier, gain narrowing remains a limiting factor, often determining a significant increase of the pulse duration after amplification.

Gain-managed nonlinear amplification (GMNA) was quite recently introduced as an alternative strategy valid for ytterbium-doped fiber amplifiers [4]. Instead of avoiding nonlinear effects during amplification, nonlinear effects play a crucial role in this new amplification regime. The core feature of this amplifier is the interplay between self-phase modulation (SPM), which progressively broadens the pulse spectrum, and the simultaneous evolution of the gain spectrum of the amplifier, which changes along the fiber while the gain is progressively saturated by the traveling pulse. If the characteristics of the seed pulse are properly chosen, this results in a smooth, monotonic chirp that can be removed with a standard grating compressor. While GMNA can substantially exceed the gain-narrowing limit of conventional fiber amplifiers, it remains subject to practical constraints of its own, most notably stimulated Raman scattering, which ultimately limits the achievable pulse energy. This approach has proven robust to a wide range of seed characteristics, including different temporal and spectral shapes, repetition rates, and pulse energies [5], indicating that the properties of the seed oscillator play a decisive role in the resulting amplifier performance. In this context, stable passive mode-locking, well-defined spectral characteristics, and reliable, self-starting pulse generation are essential prerequisites for efficient and repeatable

nonlinear amplification.

The research group of the Laser Source Lab, where I carried out my thesis work, has worked extensively in the last five-ten years on the development of reliable, state-of-the-art femtosecond fiber oscillators and fiber amplifiers.

A fully fiber-based architecture, in which both the seed oscillator and the amplifier are realized in fiber, is in principle an attractive solution, owing to its compactness, alignment-free operation, and potential for a fully monolithic, robust system. However, it is very difficult with mode-locked fiber oscillators to achieve a pulse repetition rate much higher than a few tens of megahertz. Indeed, as discussed in Chapter 1, the repetition rate of a mode-locked laser scales inversely with the cavity optical length; therefore, reaching a repetition rate of several tens of megahertz requires a cavity optical length of only a few meters. E.g., given the refractive index of silica fibers ($n \simeq 1.5$), a standing-wave mode-locked fiber laser operating at only a 40 MHz pulse repetition rate has a physical length of the whole fiber.

$$f_{rep} = \frac{c}{2nL_f} \quad \rightarrow \quad L_f = \frac{c}{2nf_{rep}} \sim 2.5 \text{ m}$$

A fiber oscillator requires the cavity to simultaneously accommodate a sufficient length of doped fiber for pump absorption and gain, together with additional fiber components for mode-locking, output coupling, and monitoring. Hence, it is impractical to scale the pulse repetition rate in fiber oscillators.

On the other side, for some applications, it is interesting to investigate a pulse repetition rate in the order of 50-100 MHz, with mode-locked femtosecond oscillators capable of producing pulses with energy in the nJ range. Indeed, this corresponds to an available average power of several tens of mW, which is enough to drive to saturation a single fiber amplifier stage pumped by a low-cost, single-emitter pump diode of 10 W power. This would lead to the realization of a master oscillator power amplifier (MOPA) system capable of delivering several watts of average power with possibly sub-100-fs pulses and MW peak power. Such a laser system can be employed directly or can be used, for instance, as the pump source for a nonlinear frequency down conversion by parametric processes.

With this target in mind, we opted for the design of a hybrid architecture combining

a bulk solid-state oscillator, providing direct and flexible control over the target repetition rate, followed by a fiber-based GMNA amplifier stage.

To this purpose, I designed, built, and characterized a femtosecond SESAM mode-locked Yb:KYW bulk laser oscillator operating at a ~ 60 MHz pulse repetition rate around a 1040 nm central output wavelength, intended as the seed source for a GMN fiber amplifier. Yb:KYW was selected as the gain medium for its broad emission bandwidth and strong absorption near 980 nm, well matched to widely available single-mode diode pump sources [6, 7]. To assess the best configuration for the mode-locked seeder, we also investigated the effect of seeder pulse duration and spectral width on the characteristics of the amplified pulses after pulse compression. Since the amplifier was working in a saturated regime, the average output power obtained after amplification was almost independent of the peculiar characteristics of the seeder pulse duration and spectrum. However, the amplified pulse duration and pulse quality after compression are actually influenced by the seed pulse duration and spectrum due to the peculiar characteristics of the nonlinear amplification regime we triggered in the fiber amplifier.

The thesis is organized as follows.

- In Chapter 1 I review the operating principles of femtosecond mode-locked oscillators, with emphasis on SESAM-based passive mode-locking.
- In Chapter 2 I introduce ultrashort-pulse amplification techniques, focusing on the theoretical background of gain-managed nonlinear amplification.
- In Chapter 3 I describe the design, ABCD-matrix analysis, assembly, and experimental characterization of the Yb:KYW oscillator, from continuous-wave operation to optimized soliton mode-locking.
- In Chapter 4 I present the implementation of the GMNA stage, including the free-space coupling scheme, the alignment procedure, and the experimental verification of the amplifier and pulse-compression performance.
- In the Conclusions, I summarize the main aspects and results of my work and discuss the future developments of this research project.

1 Femtosecond Mode-Locked oscillators

This chapter introduces the theoretical background required to understand the design and operation of the femtosecond mode-locked oscillator developed in this thesis. The concept of mode-locking is first introduced, together with the distinction between active and passive techniques. Particular attention is then devoted to passive mode-locking based on semiconductor saturable absorber mirrors (SESAMs), the technology adopted in the experimental implementation described in Chapter 3. The soliton mode-locking regime, relevant to the operation of the oscillator realized in this work, is discussed next, followed by an overview of the gain media commonly employed in femtosecond bulk oscillators, with particular focus on ytterbium-doped crystals. Finally, the chapter addresses the Q-switched mode-locking instability, establishing the theoretical stability criterion that will be applied to the specific oscillator design in Chapter 3.

1.1 Principles of mode-locking

A mode-locked laser is a resonant optical system in which a fixed phase relationship is established among a set of longitudinal cavity modes. In a free-running laser, the longitudinal modes oscillate with independent relative phases, and their incoherent superposition produces a continuous-wave output. When the phases of a sufficiently large number of longitudinal modes are locked together, the modes interfere constructively only at regularly spaced instants in time while interfering destructively elsewhere, resulting in the formation of a periodic train of short

optical pulses rather than a continuous output [8].

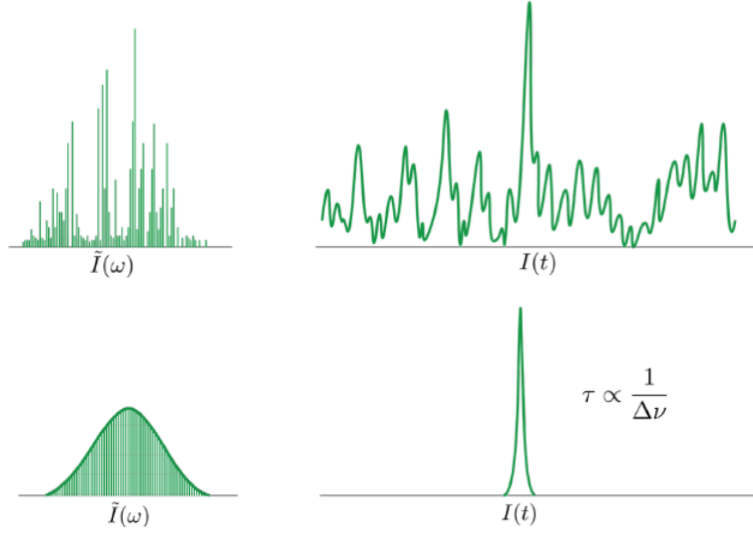


Figure 1.1: Comparison between a multimode field with random relative phase (top) and one with locked relative phase (bottom). Adapted from Fig. 6.1 (p. 226) in [9].

As shown in Fig. 1.1 in the absence of mode-locking, the spectral components interfere with uncorrelated phases, producing a noise-like temporal intensity. When the relative phase is fixed, the modes interfere constructively at regularly spaced instants, producing a clean, periodic pulse train with duration $\tau_p \propto 1/\Delta\nu_p$. The temporal periodicity of the pulse train is determined by the longitudinal mode spacing, which is set by the cavity round-trip time. The repetition frequency can therefore be expressed as

$$f_{\text{rep}} = \frac{1}{T_{\text{RT}}}, \quad (1.1)$$

where T_{RT} is the cavity round-trip time. For a linear cavity of optical length L , this relation can be written as

$$f_{\text{rep}} = \frac{c}{2L}, \quad (1.2)$$

where c is the speed of light in a vacuum. The longitudinal modes are separated in frequency by the same amount, such that

$$\Delta f = f_{\text{rep}}. \quad (1.3)$$

this relation between cavity length and repetition rate provides a first design

constraint for the oscillator developed in Chapter 3.

The achievable pulse duration is fundamentally related to the number of phase-locked longitudinal modes and to the available optical bandwidth. A broader spectrum allows a shorter pulse to be generated, provided that the spectral components possess the appropriate relative phases. For any given pulse shape, the pulse duration $\Delta\tau_p$ and the spectral bandwidth $\Delta\nu$ cannot be reduced independently but satisfy a lower bound of the form

$$\Delta\tau_p \Delta\nu \geq K, \quad (1.4)$$

where K is a numerical constant, of order unity, that depends on the assumed temporal pulse shape [10]. The quantity $\Delta\tau_p \Delta\nu$ is referred to as the time-bandwidth product (TBP), and a pulse satisfying Eq. (1.4) with equality is said to be transform limited, reaching the shortest duration allowed by its spectral bandwidth. This condition, together with the specific TBP value for a sech^2 pulse shape, will be used in Section 3.7.3 to assess the temporal quality of the mode-locked pulses generated by the oscillator.

1.2 Active vs. passive mode-locking

Mode-locking can be implemented through either active or passive mechanisms, which differ in the physical origin of the periodic loss or phase modulation that synchronizes the cavity modes. In active mode-locking, an externally driven modulator periodically modulates the intracavity loss or phase at a frequency synchronized with the cavity round-trip time. This periodic modulation preferentially reinforces the temporal region synchronized with the modulation, progressively shaping a pulse train out of the initial noise-like intracavity field [9]. Because the achievable pulse duration is ultimately limited by the speed of the modulator and by the curvature of the loss modulation near its minimum, active mode-locking alone typically yields pulse durations in the picosecond range, even though it can be combined with self-phase modulation and dispersion to shorten the pulses

further [8]. In passive mode-locking, the periodic modulation is instead produced by an intensity-dependent intracavity element, such as a saturable absorber, rather than by an external drive. High-intensity portions of the optical field experience lower losses than low-intensity fluctuations, providing an intrinsic, all-optical mechanism for pulse formation and stabilization. Since the response of a saturable absorber can be considerably faster than any practical electronic modulator, passive mode-locking is the technique of choice for femtosecond pulse generation, and it is generally self-starting, without requiring an external RF synchronization system [8, 10]. The saturable-absorber technology adopted for the oscillator developed in this thesis, and its self-starting behavior observed experimentally, are discussed in Section 1.3 and in Section 3.7.1, respectively.

1.3 Saturable absorbers and SESAM technology

Passive mode-locking requires an intensity-dependent loss mechanism capable of discriminating between low- and high-intensity portions of the intracavity field. A saturable absorber exhibits high absorption at low optical intensity, while its absorption progressively decreases as the incident fluence approaches and exceeds a characteristic saturation fluence. As a result, intense temporal fluctuations experience lower round-trip losses than the surrounding low-intensity background, providing the self-amplitude modulation required to initiate and sustain pulse formation [11].

A real saturable absorber is not fully described by its saturation fluence alone. Its behavior is characterized by a small set of parameters: the modulation depth, which sets the maximum change in loss between the unsaturated and fully saturated state; the nonsaturable loss, an intensity-independent residual loss that cannot be recovered even at high fluence; and the recovery time, which describes how quickly the absorption returns to its unsaturated value after saturation. The relative magnitude of the recovery time compared to the pulse duration distinguishes a fast saturable absorber, which relaxes on a timescale shorter than or comparable to the pulse, from a slow saturable absorber, whose relaxation extends well beyond

the pulse duration [11]. Somewhat counterintuitively, stable femtosecond pulse formation can still be obtained with a comparatively slow absorber, provided that an additional fast pulse-shaping mechanism becomes dominant once mode-locking is established; this regime, relevant to the oscillator developed in this thesis, is discussed in Section 1.4.

A semiconductor saturable absorber mirror (SESAM) implements this intensity-dependent loss in a compact, reflective device combining a semiconductor absorber structure, typically based on quantum wells or quantum dots, with a highly reflective mirror, most commonly a distributed Bragg reflector. Growing the absorber and mirror sections by epitaxial techniques allows the key parameters of the device, namely modulation depth, saturation fluence, nonsaturable loss, and recovery time, to be engineered largely independently of one another, for instance, through the absorber bandgap, layer thickness, and post-growth ion implantation [11]. This design flexibility, together with the possibility of directly integrating the absorber as one of the cavity end mirrors, has made the SESAM one of the most established and reliable technologies for the self-starting passive mode-locking of diode-pumped solid-state lasers, including the SESAM-mode-locked Yb:KYW oscillator realized in Chapter 3.

1.4 Soliton mode-locking regime

In a passively mode-locked laser, the pulse evolution over one cavity round trip results from the combined action of gain, loss, group-velocity dispersion (GVD), and optical nonlinearities. When the cavity operates in the anomalous-dispersion regime, the temporal broadening associated with negative GVD can be balanced by self-phase modulation (SPM), which introduces an intensity-dependent spectral phase that partially compensates for the linear phase accumulated from dispersion. Under this balance, a stable, chirp-free pulse can circulate in the cavity, closely resembling the fundamental soliton solution of the nonlinear Schrödinger equation [12, 13]. This soliton-shaping mechanism operates in addition to, and largely independently of, the saturable absorber. Once the soliton balance between SPM

and GVD is established, it becomes the dominant process determining the pulse duration and shape, while the saturable absorber is mainly responsible for mode-locking self-starting and for stabilizing the soliton against small perturbations and residual continuum radiation [12]. This decoupling is what allows stable femtosecond pulses to be generated even with a comparatively slow SESAM, as anticipated in Section 1.3: the absorber does not need to directly shape the pulse on a femtosecond timescale, provided that its response is fast enough to discriminate the leading edge of the pulse from the noise-like background from which mode-locking initially develops.

The soliton regime also provides a useful and experimentally verifiable relation between pulse duration and intracavity dispersion. For a fundamental soliton, the peak intracavity intensity I_0 and the pulse duration T_0 satisfy

$$I_0 T_0^2 = \frac{c |\beta_2|}{n_2 \omega}, \quad (1.5)$$

where β_2 is the group-velocity dispersion parameter, n_2 is the nonlinear refractive index of the gain medium, and ω is the optical angular frequency [14]. Equation (1.5) shows that, for a fixed intracavity dispersion, decreasing the peak intensity broadens the pulse, while increasing the magnitude of the anomalous dispersion at fixed intensity has the same effect. Both mechanisms provide practical degrees of freedom for tailoring the output pulse duration of a soliton mode-locked oscillator without altering the saturable-absorber parameters, and both are exploited in the design and optimization of the oscillator developed in Chapter 3.

1.5 Gain media for femtosecond bulk oscillators

The choice of gain medium is one of the most consequential decisions in the design of a femtosecond bulk oscillator, since it simultaneously constrains the achievable pulse duration, the available output power, and the practicality of the pumping scheme. As discussed in Section 1.1, the shortest attainable pulse duration is set by the available gain bandwidth through the time-bandwidth product of Eq. (1.4);

a narrow-band gain medium can therefore only support comparatively long pulses, regardless of how effective the mode-locking mechanism itself is. In addition to gaining bandwidth, favorable thermal conductivity and a low quantum defect between the pump and laser photon energies are essential to limit heat generation in the crystal, which would otherwise distort the intracavity mode and degrade the beam quality, as discussed in the cavity mode analysis of Chapter 3.

Rare-earth-doped crystals are the most widely employed gain media for femtosecond bulk oscillators, owing to their sharp, well-characterized energy levels and long upper-state lifetimes. Among these, ytterbium-doped materials have become particularly attractive for high-power operation. Because the Yb^{3+} ion has only two electronic manifolds, $^2F_{7/2}$ and $^2F_{5/2}$, it is free from the excited-state absorption and upconversion losses that limit many other rare-earth-doped systems, at the cost of a quasi-three-level laser scheme in which reabsorption at the laser wavelength must be overcome by sufficiently intense pumping [7]. The small energy gap between the pump and laser transitions, with diode pumping typically available near 976–980 nm, also results in a low quantum defect and correspondingly reduced thermal loading compared to other common laser ions. Various Yb-doped host crystals have been investigated for femtosecond bulk oscillators, differing mainly in emission bandwidth, thermal conductivity, and emission cross section. Hosts offering a narrow but intense emission peak, such as Yb:YAG, favor high-efficiency and power scaling but support only comparatively long pulses, whereas hosts with a broader and smoother emission band, such as Yb:CaF₂ or Yb-doped tungstates, trade some efficiency and thermal conductivity for the bandwidth required to sustain shorter pulses [7, 15]. Yb-doped potassium tungstates, in particular Yb:KYW and Yb:KGW, combine a broad and comparatively smooth emission band around 1 μm with favorable spectroscopic properties, and have been successfully employed as gain media in SESAM-mode-locked bulk oscillators delivering pulse durations well below one picosecond [16]. The Yb:KYW crystal adopted for the oscillator developed in this thesis, together with the specific spectroscopic properties relevant to its selection, is discussed in detail in Section 3.1.

1.6 Q-switched mode-locking instabilities

Satisfying the resonator stability condition and providing sufficient net gain, as discussed in Chapter 3, is not by itself sufficient to guarantee stable continuous-wave (cw) mode-locking in a SESAM-based passively mode-locked oscillator. The interplay between gain saturation and the finite saturation energy of the absorber can give rise to a distinct instability, known as Q-switched mode-locking (QSML). In SESAM-based oscillators, QSML instabilities may occur when the intracavity pulse energy is insufficient to saturate the absorber and stabilize the mode-locking process. In this regime, the laser emits bursts of ultrashort pulses modulated by a low-frequency Q-switched envelope, leading to large pulse-to-pulse energy fluctuations. Besides degrading the laser performance, QSML operation may expose the SESAM to excessive peak intensity and increase the risk of optical damage.

A qualitative comparison between stable mode-locking and QSML operation is shown in Fig. 1.2.

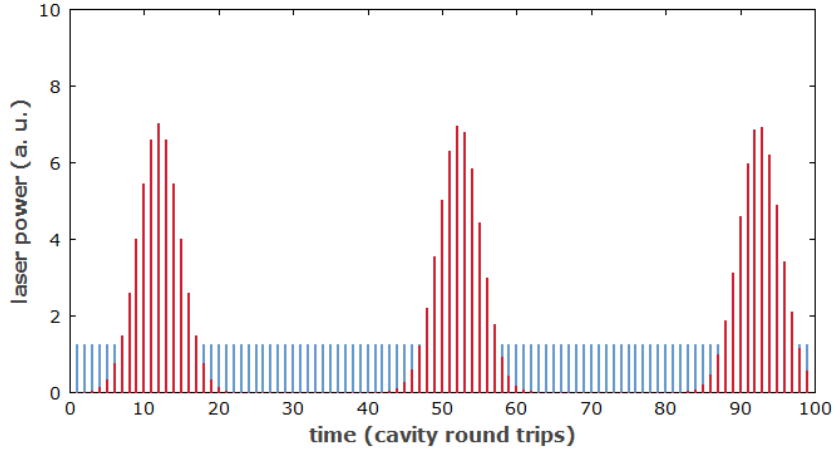


Figure 1.2: Evolution of the optical power in a passively mode-locked oscillator operating in the Q-switched mode-locking regime (red), where bunches of ultrashort pulses are generated, and in the stable mode-locking regime (blue), characterized by a constant pulse energy. [17]

The transition between these two operating regimes can be described in terms of a critical intracavity pulse energy. According to the theoretical model developed for soliton mode-locked oscillators with slow saturable absorbers [18] and subsequently

applied to a range of SESAM-mode-locked Yb-doped bulk oscillators [7], stable passive mode-locking requires the intracavity pulse energy to exceed a critical value E_{crit} , given by

$$E_{\text{crit}} = -\frac{g\xi^2 E_{\text{sat,L}}}{2} + \sqrt{\left(\frac{g\xi^2 E_{\text{sat,L}}}{2}\right)^2 + E_{\text{sat,L}} E_{\text{sat,S}} \Delta R} \quad (1.6)$$

where g is the saturated gain that equals the cavity losses above the laser threshold, $E_{\text{sat,L}}$ is the saturation energy of the gain medium, $E_{\text{sat,S}}$ is the saturation energy of the SESAM, ΔR is the SESAM modulation depth, and ξ represents the fraction of the available gain bandwidth participating in pulse formation.

The saturation energy of the gain medium is related to its saturation fluence according to

$$E_{\text{sat,L}} = F_{\text{sat,L}} \cdot A_L \quad (1.7)$$

where A_L is the laser mode area inside the gain medium. The saturation fluence can be calculated from the absorption and emission cross sections as

$$F_{\text{sat,L}} = \frac{h\nu}{\sigma_e + \sigma_a} \quad (1.8)$$

where h is Planck's constant, ν is the optical frequency, and σ_e and σ_a are the emission and absorption cross sections at the laser wavelength.

Assuming a Gaussian beam profile, the mode area is

$$A_L = \pi w_L^2 \quad (1.9)$$

where w_L is the intracavity mode radius in the gain medium.

Similarly, the SESAM saturation energy can be written as

$$E_{\text{sat,S}} = F_{\text{sat,S}} A_S, \quad (1.10)$$

where $F_{\text{sat,S}}$ is the SESAM saturation fluence, which is a design parameter of the saturable absorber, and

$$A_S = \pi w_S^2 \quad (1.11)$$

is the beam area on the SESAM, with w_S denoting the corresponding mode radius. The intracavity pulse energy can be estimated from the measured average output power according to

$$E_{\text{cav}} = \frac{P_{\text{out}}}{f_{\text{rep}} T_{\text{OC}}}, \quad (1.12)$$

where P_{out} is the average output power, f_{rep} is the pulse repetition frequency, and T_{OC} is the transmission of the output coupler. The condition for stable passive mode-locking can therefore be expressed as

$$E_{\text{cav}} > E_{\text{crit}}. \quad (1.13)$$

Equation (1.13) provides a useful design criterion for the selection of the SESAM parameters, the output coupling, and the intracavity mode sizes. This criterion is applied to the specific oscillator developed in this thesis in Section 3.4 of Chapter 3, where the quantities appearing in Eqs. (1.7)–(1.12) are evaluated using both the cavity-design parameters and the experimentally measured values.

2 Ultrashort pulse Amplifiers

This chapter reviews the theoretical background of ultrashort-pulse amplification, motivating the transition from the mode-locked oscillator described in Chapter 1 to the amplification stage implemented in Chapter 4. The need for optical amplification is first discussed, followed by an overview of chirped-pulse amplification (CPA), the conventional approach widely adopted in high-energy ultrafast laser systems. The physical limitations that motivate an alternative strategy for fiber-based amplifiers, namely gain narrowing and the accumulation of nonlinear phase, are then examined. Gain-managed nonlinear amplification (GMNA), the technique adopted for the amplifier realized in this work, is introduced as a strategy that exploits rather than avoids these effects. Eventually, the theoretical principles of pulse compression by diffraction-grating pairs are reviewed, providing the background for the compression stage implemented in the lab and described in Chapter 4.

2.1 Motivation for pulse amplification

As discussed in Chapter 1, a mode-locked oscillator directly generates ultrashort pulses with excellent temporal and spectral quality, but only at comparatively low pulse energies. The oscillator developed in this thesis, for instance, delivered pulses with an energy of approximately 1 nJ (Table 3.2), a value representative of typical low-power, diode-pumped bulk oscillators.

Many applications of ultrafast lasers, however, require pulse energies several orders of magnitude higher than those directly available from an oscillator. For example, frequency comb generation via supercontinuum broadening requires

peak powers sufficient to drive efficient nonlinear interactions, while precision materials processing exploits high peak intensities to achieve clean, thermally confined material removal [1]. Bridging this gap between the pulse energy directly available from an oscillator and that required by the target application is the role of the amplification stage.

A fundamental challenge in amplifying ultrashort pulses is that increasing the pulse energy while preserving a short pulse duration correspondingly increases the peak intensity, which can readily exceed the damage threshold of the amplifying medium or trigger uncontrolled nonlinear effects, most notably SPM, well before the target energy is reached. Any amplification strategy for femtosecond pulses must therefore explicitly manage this trade-off between energy scaling and peak-power-driven distortion, either by avoiding high peak intensities during amplification, as in CPA (Section 2.2), or by deliberately incorporating the resulting nonlinear evolution into the amplification process itself, as in the GMNA scheme adopted in this work (Section 2.4).

2.2 Chirped-pulse amplification

CPA is the conventional strategy adopted to amplify ultrashort pulses to high energy while avoiding the nonlinear distortion and optical damage discussed in Section 2.1. The central idea of CPA is to temporarily reduce the peak intensity of the pulse during amplification, rather than to amplify it directly at its original, transform-limited duration.

In a CPA system, the seed pulse is first temporally stretched, typically by several orders of magnitude, using a dispersive element such as a grating or fiber-based stretcher that imparts a large, possibly linear chirp. Because the pulse energy is conserved while its duration is increased, the peak power of the stretched pulse is correspondingly reduced, often by three to four orders of magnitude relative to the original pulse. The stretched, low-peak-power pulse can then be amplified to much higher energy without exceeding the damage threshold of the gain medium or accumulating a significant, uncontrolled nonlinear phase. After amplification, a

matched dispersive compressor, providing group-delay dispersion of opposite sign to that introduced by the stretcher, removes the imparted chirp and recompresses the pulse close to its original, transform-limited duration, now at a much higher energy.

Since its introduction, CPA has enabled the scaling of ultrafast laser systems to pulse energies and peak powers far beyond what is achievable with a single amplification stage and remains the standard approach for high-energy femtosecond and picosecond amplifiers. The technique, however, requires a stretcher and a compressor with closely matched and typically opposite-sign dispersion characteristics, adding complexity and, particularly in fiber-based systems, a comparatively long length of fiber or free-space optics dedicated purely to stretching and recompressing the pulse rather than to gain. This motivates the search for amplification strategies that can reduce or eliminate the need for a dedicated stretching stage, as discussed in Section 2.3.

2.3 Gain narrowing and nonlinear effects in fiber amplifiers

Gain narrowing arises because the gain provided by a doped fiber amplifier has a finite bandwidth. As a pulse propagates through the amplifier, spectral components near the peak of the gain curve experience more amplification than those in the wings so that the amplified spectrum progressively narrows relative to the seed spectrum. Since the achievable pulse duration after compression is ultimately bounded by the time-bandwidth product of the amplified spectrum (Eq. (1.4)), gain narrowing directly limits the shortest pulse duration obtainable from a fiber CPA system, regardless of how the stretching and compression stages are designed [4].

In addition to gain narrowing, the small effective mode area of a single-mode fiber, typically on the order of a few hundred square micrometers or less even for large-mode-area designs, makes fiber amplifiers considerably more susceptible to self-phase modulation (SPM) than bulk amplifiers of comparable gain. The

nonlinear phase accumulated by a pulse of peak power $P(z)$ propagating through a fiber of nonlinear parameter $\gamma = 2\pi n_2/(\lambda A_{\text{eff}})$ can be estimated as

$$\phi_{\text{NL}} = \gamma \int_0^L P(z) dz, \quad (2.1)$$

where n_2 is the nonlinear refractive index of the fiber core, A_{eff} is the effective mode area, and L is the fiber length [14]. Even under CPA, where the pulse is stretched to reduce its peak power, the combination of long interaction length and small mode area in a fiber amplifier means that ϕ_{NL} can approach or exceed a few radians well before the target output energy is reached, at which point the compressed pulse deviates significantly from its transform limit and develops pedestals or a distorted temporal profile.

Conventional fiber CPA amplifiers must therefore be designed to keep the nonlinear phase small, typically by employing large stretch ratios, large-mode-area fibers, or a combination of both, while simultaneously being limited in achievable bandwidth by gain narrowing. These two constraints act in opposition: measures that reduce nonlinear phase accumulation, such as increasing the mode area or the stretch ratio, do not relax the gain-narrowing limitation and can in some cases make it more pronounced by requiring a longer or higher-gain amplifying fiber. This combined limitation on the energy and bandwidth simultaneously achievable in a fiber CPA amplifier motivates an alternative approach, in which the nonlinear evolution of the pulse is not suppressed but is instead deliberately incorporated into the amplification process, as discussed in Section 2.4.

2.4 Gain-managed nonlinear amplification

GMNA was introduced by Sidorenko et al.[4] as a strategy to circumvent the combined gain-narrowing and nonlinear-phase limitations of conventional fiber CPA discussed in Section 2.3, by eliminating the stretcher stage altogether and allowing the seed pulse to accumulate a controlled amount of nonlinear phase directly during amplification. In a GMNA system, a comparatively low-energy,

near-transform-limited seed pulse is launched directly into a normal-dispersion, ytterbium-doped fiber without any prior temporal stretching.

The evolution of the pulse envelope $A(z, T)$ along the active fiber can be described by a generalized nonlinear Schrödinger equation with a longitudinally varying, saturable gain term,

$$\frac{\partial A}{\partial z} = -i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} + i\gamma|A|^2A + \frac{g(z)}{2}A, \quad (2.2)$$

where $\beta_2 > 0$ is the (normal) group-velocity dispersion of the fiber, γ is the nonlinear parameter introduced in Eq. (2.1), and $g(z)$ is the saturable gain coefficient, obtained from the population-inversion rate equations rather than assumed to be a fixed, spatially uniform value [4].

2.4.1 Pulse evolution toward the nonlinear attractor

Numerical simulations of Eq. (2.2) presented in [4] reveal that the GMNA regime is reached only after the pulse evolution is allowed to proceed beyond the point traditionally regarded as the limit of useful amplification. A seed pulse launched into a highly doped Yb-doped fiber initially evolves toward a self-similar pulse, or "similariton," as dispersive and nonlinear effects reshape it into a parabolic temporal and spectral profile. As the pulse energy and bandwidth continue to grow, gain-shaping begins to impede this self-similar growth, and the pulse experiences the nonlinear distortions that, in conventional soliton amplifier design, are taken as the practical limit of the technique. If the propagation is allowed to continue further, however, a new, stable regime emerges: the pulse spectrum shifts progressively toward longer wavelengths, developing a pronounced asymmetric shape, while a smooth, largely monotonic chirp develops that can subsequently be compensated for with a simple grating compressor [4].

The physical origin of this spectral asymmetry is directly connected to the quasi-three-level nature of Yb-doped gain media discussed in Section 1.5 and modeled explicitly for the oscillator design in Section 3.4: as the pulse spectrum broadens through self-phase modulation, its blue edge encounters the residual ground-state

absorption near the seed wavelength, which is progressively bleached and redshifted as the pulse co-propagates with the evolving inversion, while the red edge of the spectrum continues to broaden largely unimpeded by gain or loss. This asymmetric confinement of the blue side of the spectrum, together with the unhindered growth of the red side, is the origin of the characteristic redshifted, asymmetric output spectrum of a GMNA amplifier, and explains why an accurate model of the amplifier must include the true, rate-equation gain rather than a simplified, spectrally uniform saturable gain [4].

A further distinctive, and initially counterintuitive, feature of the GMNA regime is that the pulse peak power does not grow monotonically with propagation distance, unlike in essentially every other established amplification regime. The peak power initially increases as the pulse approaches the self-similar attractor, but as the accumulating bandwidth increases the effect of dispersion while the available gain is progressively depleted by pump absorption, the peak power reaches a maximum and subsequently decreases, even as the pulse energy continues to grow monotonically due to the increasing pulse duration [4].

2.4.2 Distinction from self-similar (similariton) amplification

Although the GMNA regime emerges from an evolution that initially resembles self-similar amplification, it is fundamentally different in the way gain shapes the pulse and in its longitudinal scaling behavior. Self-similar amplification is generally understood to be incompatible with significant gain-shaping: a similariton distorts and loses its self-similar character once the gain spectrum departs substantially from a fixed, homogeneously broadened profile. The GMNA regime exists only in the opposite limit, in which strong, longitudinally evolving gain-shaping, including both amplification and reabsorption of different parts of the spectrum, is essential to the pulse-forming mechanism [4].

The two regimes are also distinguished by their characteristic growth laws. A similariton is characterized by the exponential growth of its energy, duration, peak power, and bandwidth with propagation distance. A pulse in the GMNA regime, by contrast, grows appreciably only in duration; its energy and spectral

bandwidth instead saturate to comparatively stable values, while its peak power, as discussed above, reaches a maximum and subsequently decreases [4].

The robustness of the GMNA output to the specific characteristics of the seed pulse provides further, independent evidence that the regime is governed by a nonlinear attractor rather than by the particular properties of the input. Numerically, seed pulses spanning a wide range of shapes, durations, energies, and chirps were shown to converge, at a common point in their evolution identified by the pulse peak power, to essentially the same output pulse [4]. Experimentally, this insensitivity to the seed was confirmed both by varying the seed pulse energy by nearly a factor of three at a fixed spectral shape and by varying the seed bandwidth and duration at fixed energy, in both cases without requiring any adjustment of the pump power or of the grating compressor to recover a comparable, near-transform-limited output pulse [4]. A similar robustness to markedly different seed characteristics, including repetition rate, was subsequently reported for a distinct Yb-fiber GMNA system [5], further supporting the generality of the attractor picture. This robustness to the seed characteristics is particularly relevant to the present work, since the oscillator developed in Chapters 1–3 was deliberately optimized for a comparatively narrow, soliton-limited spectrum rather than for maximum bandwidth, as discussed in Section 3.7.3.

2.4.3 Practical limitations: stimulated Raman scattering and energy scaling

Although GMNA removes the need for a dedicated stretching stage, it does not remove the fundamental trade-off between pulse energy and peak intensity described in Section 2.1: since the pulse is never stretched, its peak power inside the active fiber remains comparatively high throughout the amplification process. This makes stimulated Raman scattering (SRS) the practical mechanism that ultimately limits the achievable pulse energy in a GMNA amplifier based on a standard single-mode fiber. In the original demonstration of GMNA, a low-intensity Raman shoulder was first observed at a signal energy of approximately 68 nJ; however, this

contribution remained a minor fraction of the total pulse energy, below 3%, even at the highest pulse energy detailed in the main demonstration, 107 nJ where the amplified pulse was compressed to 42 fs with 89% of the energy contained in the main pulse. Stable operation at 200 nJ and 40 fs was subsequently demonstrated in the same work, with numerical simulations indicating that pulse energies as high as 300 nJ, compressible to 30 fs, should be achievable with increased pump power [4].

Since the Raman gain experienced by the signal scales with its intensity rather than its energy, a direct strategy to raise the SRS threshold and enable further energy scaling is to increase the effective mode area of the active fiber, thereby reducing the peak intensity for a given pulse energy; the authors of the original GMNA demonstration explicitly identified this as a promising direction, while noting that pump absorption in a double-clad, large-mode-area fiber could affect the longitudinal gain evolution in a non-trivial way, potentially leading to scaling relations more complex than a simple mode-area argument would suggest [4]. This extension was subsequently demonstrated by Sidorenko and Wise using a large-mode-area, Yb-doped fiber, yielding compressed pulses with energies of 1.2 μJ and durations below 40 fs while preserving the same underlying gain-nonlinearity coupling [19].

A further practical consequence of the coupled gain-nonlinearity dynamics is that, unlike the largely independent design of the stretcher, amplifier, and compressor stages in a conventional CPA system, the spectral and temporal evolution of the pulse in a GMNA amplifier cannot in general be predicted from simple analytical scaling laws; indeed, an analytical solution of the nonlinear Schrödinger equation coupled with the gain rate equations has not yet been found [4]. Reliable design of a GMNA stage therefore typically relies on numerical integration of Eq. (2.2) together with the amplifier rate equations, rather than on closed-form design rules, so that the achievable pulse energy, bandwidth, and duration for a given fiber, pump power, and seed condition are generally established through a combination of simulation and experimental optimization, as was the case for the amplifier implemented in Chapter 4.

2.5 Pulse compression techniques

As discussed in Section 2.4, a pulse amplified in the GMNA regime emerges from the active fiber with a substantially broadened optical spectrum but also with a large, predominantly positive chirp accumulated from self-phase modulation and normal group-velocity dispersion during propagation. Recovering a short pulse from this broadened spectrum, therefore, requires an external dispersive element capable of introducing a comparatively large amount of negative group-delay dispersion (GDD) to compensate for the chirp and bring the pulse close to its transform limit, as defined by the time-bandwidth product of Eq. (1.4).

Among the available options for introducing large, tunable negative GDD, diffraction-grating pairs, prism pairs, and chirped mirrors are the most widely used. Chirped mirrors provide only a small amount of GDD per reflection and are therefore poorly suited to compensating for the large chirp accumulated in a GMNA amplifier without a huge number of bounces. Prism pairs can provide continuously tunable dispersion with low insertion loss, but the achievable magnitude of negative GDD for a given footprint is comparatively limited. Diffraction-grating pairs, in contrast, can provide a large, continuously tunable amount of negative GDD in a compact geometry, at the expense of a higher insertion loss associated with the finite diffraction efficiency of the gratings; for this reason, a grating-pair compressor was adopted for the amplifier developed in this work, as described in Section 4.5 of Chapter 4.

2.5.1 Dispersion of a grating pair

The dispersive properties of a grating-pair compressor were first analyzed by Treacy [20]. When a broadband pulse is incident on a diffraction grating of groove spacing Λ at an angle of incidence θ_i , different spectral components are diffracted at different angles $\theta_d(\lambda)$, according to the grating equation.

$$\Lambda (\sin \theta_i + \sin \theta_d) = \lambda. \quad (2.3)$$

A second grating, placed parallel to the first at a perpendicular separation L_g , recombines the diffracted beams into a single, collimated output beam, as illustrated in the top panel of Fig. 2.1. Because longer-wavelength components travel a longer optical path between the two gratings than shorter-wavelength components, the pair introduces a wavelength-dependent group delay and, therefore, a net GDD, given by

$$\text{GDD}_{\text{pair}} = -\frac{\lambda^3 L_g}{\pi c^2 \Lambda^2 \cos^3 \theta_d}, \quad (2.4)$$

where c is the speed of light in a vacuum [20]. Equation (2.4) shows that the GDD introduced by the grating pair is always negative for a single pass, and that its magnitude scales linearly with the physical separation L_g between the gratings, providing a simple and direct means of tuning the total accumulated dispersion.

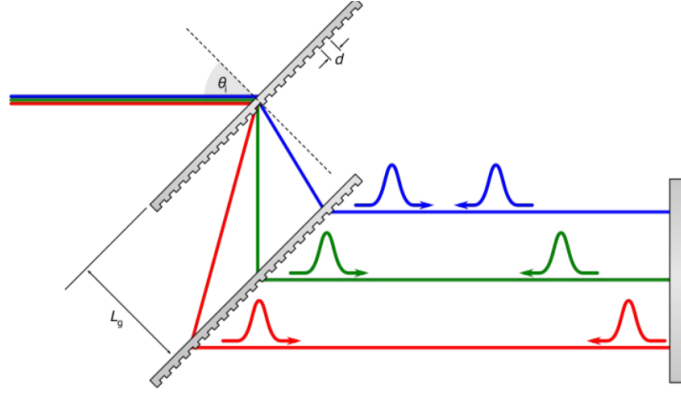


Figure 2.1: Schematic of a single-pass Treacy grating-pair compressor. Adapted from [21].

2.5.2 Double-pass configuration

For a given grating separation, the magnitude of negative GDD obtainable from a single pass through the grating pair is often insufficient to compensate for the chirp accumulated in a GMNA amplifier. A common solution, adopted for the compressor implemented in this work (Section 4.5.2), is to fold the beam back through the same grating pair using a retroreflecting element, such as a right-angle prism, so that the beam traverses the compressor twice before exiting, as shown in the bottom panel of Fig. 2.2. Since the two passes are independent and add coherently in terms of accumulated group delay, the total dispersion of a

double-pass grating compressor is simply twice that of Eq. (2.4),

$$\text{GDD}_{2\text{-pass}} = 2 \text{GDD}_{\text{pair}}, \quad (2.5)$$

allowing the same grating separation to provide twice the dispersion, or equivalently, the same total dispersion to be achieved with half the physical footprint. In practice, the grating separation L_g is adjusted experimentally, typically by mounting one of the gratings (or the retroreflecting element) on a translation stage while monitoring the compressed pulse duration, until the accumulated negative GDD closely matches the positive chirp imparted by the amplifier and the compressed pulse approaches its transform limit. This procedure, together with the temporal characterization of the resulting compressed pulses, is described in Sections 4.5.2 and 4.5.3 of Chapter 4.

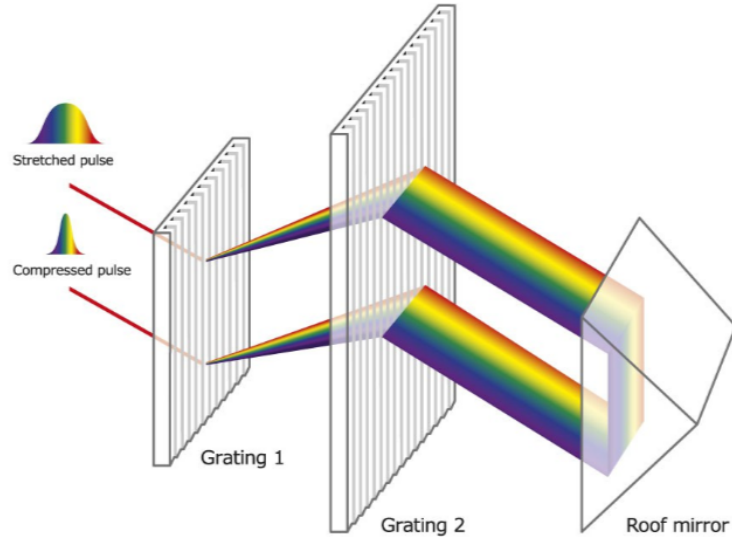


Figure 2.2: Practical double-pass implementation of the grating compressor, using a rooftop retroreflecting mirror to fold the beam back through the same grating pair. Adapted from [21].

3 Laser cavity design

This chapter describes the design process of the oscillator developed during this thesis work.

The project started from a set of predefined requirements. In particular, the aim was to realize a femtosecond laser oscillator based on an Yb-doped crystal pumped by a laser diode operating at 976 nm , providing up to 600 mW of pump power. The design requirements also included a pulse repetition rate around $60\text{--}70\text{ MHz}$, the definition of the optical cavity geometry, the selection of the mirror characteristics and coatings, the sizing of the resonant mode within the active medium, and the identification of a suitable technique for initiating and sustaining mode-locked operation.

Based on these requirements, a design procedure was established using cavity stability analysis through the ABCD matrix formalism. This approach made it possible to identify an optical layout compatible with the assigned specifications and to estimate the laser mode dimensions at the main cavity elements. The configurations obtained from the numerical analysis were subsequently implemented and experimentally verified.

3.1 Gain medium selection

The gain medium selected for the oscillator was a Yb:KYW crystal. This material is particularly suitable for femtosecond laser operation due to its relatively broad emission bandwidth, which supports the generation of ultrashort pulses, and its strong absorption around 980 nm , allowing efficient pumping with commercially available laser diodes. Yb:KYW has been widely employed in femtosecond solid-

state lasers over the last two decades, making it a well-established and readily available gain medium. Several Yb:KYW samples with different crystal lengths and ytterbium doping concentrations were available in the laboratory.

KYW is a biaxial birefringent crystal, meaning that its refractive index and spectroscopic properties depend on the polarization direction along the three principal optical axes. The highest absorption and emission cross sections are obtained for light polarized along the crystal N_m axis (Fig. 3.1). Nevertheless, a broad emission cross section is also available for polarization along the N_p axis. Since the Yb:KYW crystal employed in this work was cut for beam propagation along the N_g axis, laser oscillation occurred with polarization parallel to the N_p axis.

In addition, Yb-doped materials exhibit a simple energy level structure compared to other rare-earth ions, resulting in reduced thermal load and high quantum efficiency.

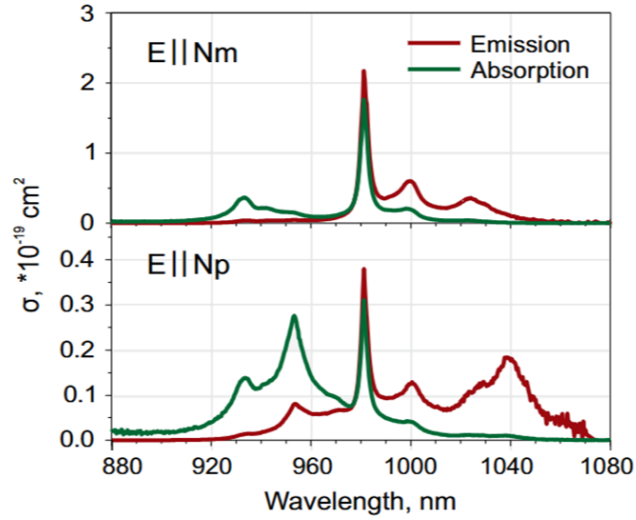


Figure 3.1: Polarized absorption and emission cross sections of Yb:KYW along the N_m and N_p optical axes. Adapted from [6].

As shown in Fig. 3.1, the absorption cross section exhibits a pronounced peak close to 981 nm for both the N_m and N_p polarizations, making the material well suited for diode pumping at this wavelength. Furthermore, although the emission cross section reaches its maximum value along the N_m axis, the N_p polarization also

provides a sufficiently broad emission bandwidth extending over the 1030–1040 nm spectral region. This bandwidth is adequate to sustain femtosecond mode-locked operation and corresponds to the polarization adopted in the oscillator developed in this work.

3.2 Preliminary cavity design

Following the selection of the gain medium, the next step consisted of defining a cavity geometry compatible with the target operating conditions. Among the design requirements, the specified pulse repetition rate of ≈ 60 MHz provided a first constraint on the overall cavity length.

For a linear resonator, the repetition rate is related to the optical cavity length through

$$f_{\text{rep}} = \frac{c}{2L} \quad (3.1)$$

where c is the speed of light and L is the total optical length of the cavity. The specified repetition-rate range, therefore, corresponds to a cavity length of about 2.5 m.

The preliminary resonator layout was based on an X-folded cavity geometry, chosen as a compromise between compactness and flexibility in the positioning of the intracavity elements. The folded configuration allows the required optical path length to be achieved while maintaining a relatively small footprint on the optical table. In addition, it enables the introduction of focusing sections within the resonator, allowing the intracavity mode to be efficiently matched to the pumped volume of the gain crystal.

At this stage of the design process, the mode-locking element was not yet included in the numerical model. Instead, the cavity was initially analyzed by considering a high-reflectivity end mirror in place of the SESAM. This simplified configuration allowed the stability properties of the resonator to be investigated independently of the mode-locking mechanism and provided a starting point for the optimization of the cavity geometry.

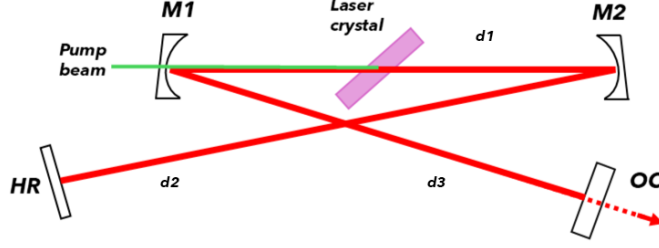


Figure 3.2: Generic X-folded linear resonator showing the main intracavity elements.

Once the preliminary cavity geometry had been established, a numerical analysis based on the ABCD matrix formalism was carried out to evaluate the resonator stability and determine the beam waist dimensions at the relevant intracavity locations.

3.3 ABCD matrix analysis

To evaluate the stability of the proposed resonator geometry and determine the characteristics of the intracavity mode, the cavity was analyzed using the ABCD matrix formalism. This approach provides a convenient framework for describing the propagation of Gaussian beams through optical systems and is widely employed in the design of laser resonators.

The optical cavity was modeled as a sequence of free-space propagation sections and reflective optical elements. The corresponding ABCD matrices were combined to obtain the round-trip matrix of the resonator, from which both the stability condition and the Gaussian beam parameters could be determined.

3.3.1 Resonator stability

The stability of the resonator was evaluated by means of the round-trip ABCD matrix

$$M = \begin{pmatrix} A & B \\ C & D \end{pmatrix}.$$

A stable resonator requires that the Gaussian eigenmode reproduce itself after successive round trips within the cavity. This condition can be expressed in terms of the half-trace of the round-trip matrix as

$$\left| \frac{A + D}{2} \right| < 1.$$

The half-trace was therefore calculated as a function of the cavity geometry to identify the resonator configurations satisfying the stability criterion.

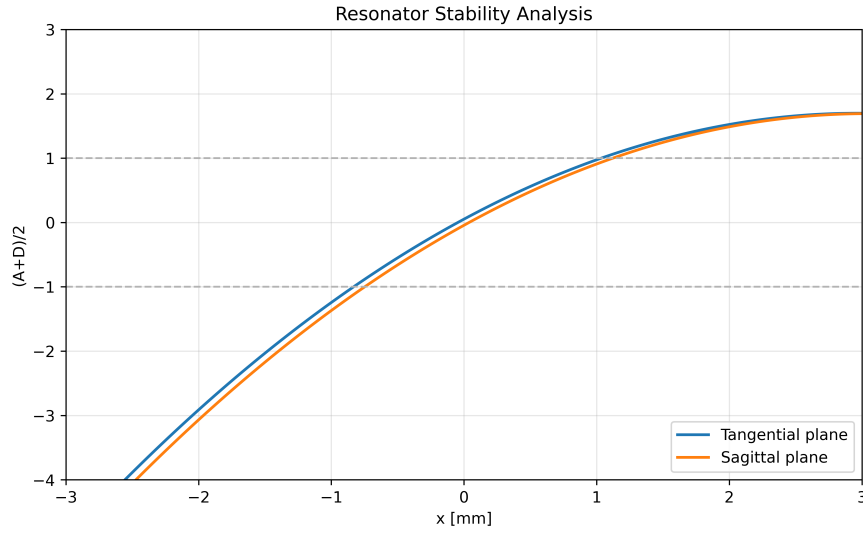


Figure 3.3: Calculated the round-trip matrix half-trace as a function of the displacement X of the folding mirror M2.

As shown in Fig. 3.2, the geometry of the resonator is mainly determined by the position of the folding mirrors. During the numerical optimization, the parameter X was introduced to represent the displacement of mirror M2 regarding its nominal position. Varying X simultaneously modifies the adjacent free-space propagation distances, thus changing the geometry of the focusing section of the cavity. The round-trip ABCD matrix was recalculated for each value of X to evaluate the sensitivity of the resonator stability to small mirror displacements.

The stability condition is satisfied whenever the half-trace remains within the interval $[-1, 1]$. As shown in Fig. 3.3, a stable operating region extending over approximately 2 mm was identified. This stability range provides a useful estimate of the alignment tolerance of the resonator and defines the interval within which

stable laser operation can be expected.

A cavity configuration located close to the center of the stability region was selected for the subsequent design stages to maximize robustness against mechanical and alignment uncertainties. As discussed in the following section, the position of mirror M2 determines the stability of the resonator and strongly influences the cavity mode size at the gain medium, the SESAM, and the output coupler. For this reason, in the experimental setup, M2 was mounted on a micrometric translation stage, allowing its position to be adjusted with a resolution of approximately $\pm 10 \mu\text{m}$.

3.3.2 Intracavity mode analysis

After identifying the stable operating region, the ABCD model was used to evaluate the Gaussian beam dimensions at the main cavity elements. The beam waist was calculated as a function of the geometrical parameter X , allowing the influence of cavity geometry on the intracavity mode to be investigated. Particular attention was devoted to three locations of practical interest: the gain crystal, the high-reflectivity end mirror (corresponding to the future SESAM position), and the output coupler. The mode size at these locations directly affects the pump-mode overlap, the fluence on the saturable absorber, and the characteristics of the output beam, respectively. Figure 3.4 shows the calculated beam waist inside the gain crystal as a function of the parameter X . As expected, the mode size varies across the stability region due to the dependence of the resonator fundamental transverse mode on the cavity geometry. The crystal waist represents a key design parameter since it determines the overlap between the intracavity mode and the pumped volume. This is crucial to obtain both single transverse mode oscillation and high optical-to-optical conversion efficiency from the pump to the laser output. The selected cavity configuration provides a mode size compatible with efficient excitation of the gain medium while preserving stable resonator operation. The beam waist calculated at the high-reflectivity end mirror is reported in Fig. 3.5. In the final implementation of the oscillator, this mirror was replaced by a SESAM to enable passive mode locking. Consequently, the

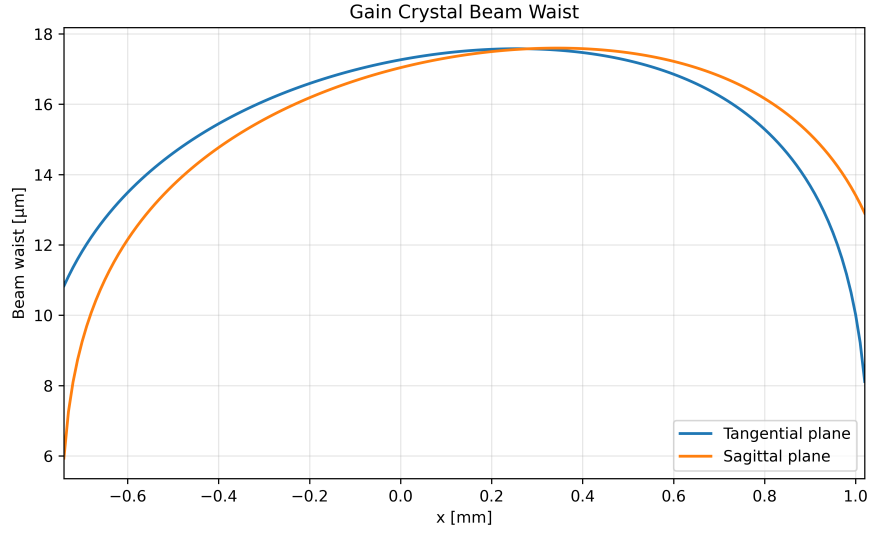


Figure 3.4: Calculated beam waist inside the gain crystal as a function of X .

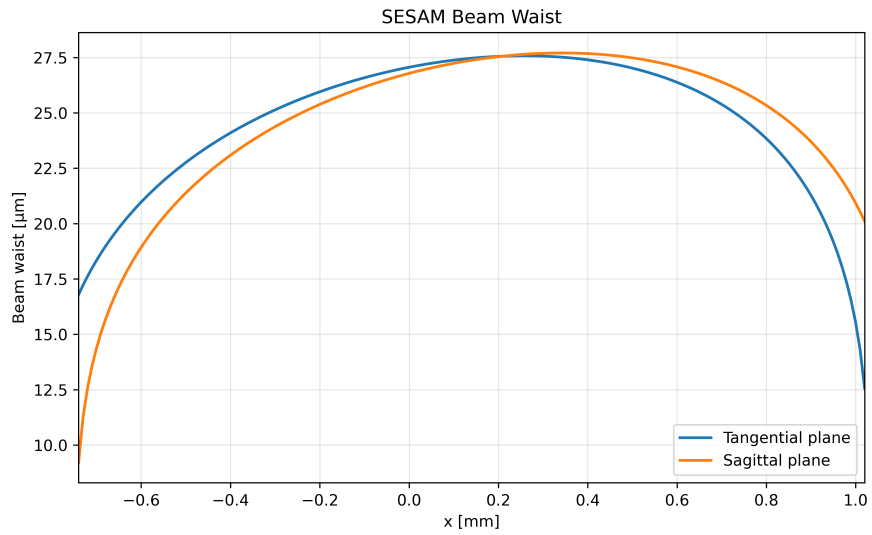


Figure 3.5: Calculated beam waist at the SESAM position as a function of X .

calculated mode size provides an estimate of the beam radius incident on the saturable absorber. The waist at this location is an important parameter since it determines the optical fluence experienced by the SESAM and therefore influences the mode-locking dynamics. Figure 3.6 reports the beam waist at the output

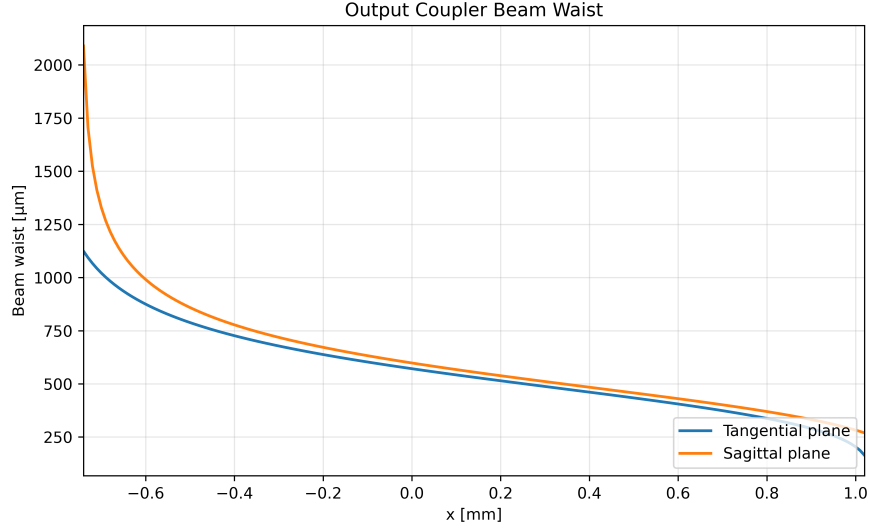


Figure 3.6: Calculated beam waist at the output coupler as a function of X .

coupler. This parameter determines the spatial characteristics of the extracted beam and was considered during the optimization of the resonator geometry.

3.4 Passive mode-locking stability criterion

Before proceeding with the experimental implementation, a preliminary theoretical verification was performed to assess the risk of Q-switched mode-locking (QSML) and to select a safe output-coupler transmission among those available in the laboratory, following the criterion introduced in Section 1.6.

3.4.1 Critical intracavity pulse energy

The critical intracavity pulse energy E_{crit} was evaluated from Eq. (1.6) using the design-stage parameters: mode radii $w_L \approx 17 \mu\text{m}$ inside the crystal and $w_S \approx 27.5 \mu\text{m}$ at the SESAM position, from the ABCD cavity analysis (Section 3.3.2); emission and absorption cross sections $\sigma_e \approx 1.4 \times 10^{-24} \text{ m}^2$, $\sigma_a \approx 0.2 \times 10^{-24} \text{ m}^2$

at 1040 nm; SESAM modulation depth $\Delta R = 2\%$ and saturation fluence $F_{\text{sat,S}} = 50 \mu\text{J}/\text{cm}^2$ (absorber datasheet); and a gain-bandwidth participation factor $\xi \approx 0.2$. With negligible additional passive losses, the saturated gain reduces to $g(T) \approx \frac{1}{2} [-\ln(1 - T)]$. This yields $E_{\text{sat,L}} \approx 108.4 \mu\text{J}$ and $E_{\text{sat,S}} \approx 1.19 \text{ nJ}$.

3.4.2 Threshold pump power: a quasi-three-level treatment

Since Yb^{3+} operates on a quasi-three-level scheme, ground-state reabsorption at the laser wavelength must be overcome before net gain can be established, in addition to compensating the cavity round-trip loss. Writing the round-trip net-gain condition for a crystal of length L and Yb^{3+} density N_{Yb} as

$$\sigma_e N_2 L - \sigma_a (N_{\text{Yb}} - N_2) L = \frac{\Gamma(T)}{2}, \quad (3.2)$$

where $\Gamma(T) = \delta - \ln(1 - T)$ is the round-trip loss parameter already appearing in $\eta_s(T)$, and combining this with the steady-state upper-level population $N_2 = \eta_0 P_{\text{pump}} \tau / (h\nu_p A_L L)$ obtained from the rate equations, the threshold pump power follows as

$$P_{\text{th}}(T) = \underbrace{\frac{h\nu_p A_L L \sigma_a N_{\text{Yb}}}{\eta_0 \tau (\sigma_e + \sigma_a)}}_{P_{\text{transp}}} + \underbrace{\frac{h\nu_p A_L}{2\eta_0 \tau (\sigma_e + \sigma_a)} \Gamma(T)}_{P_{\text{gain}}(T)}. \quad (3.3)$$

The first term, P_{transp} , is the fixed pump power required to bleach the ground-state absorption and reach transparency, independent of the output-coupler transmission; the second term, $P_{\text{gain}}(T)$, provides the additional pump power needed to overcome the cavity round-trip loss $\Gamma(T)$, and shares the same physical origin as the round-trip loss parameter entering the slope efficiency $\eta_s(T)$.

Using a crystal length $L = 2 \text{ mm}$, a doping concentration of 5 at.% (corresponding to $N_{\text{Yb}} \approx 3.19 \times 10^{26} \text{ m}^{-3}$, obtained from the $\text{KY}(\text{WO}_4)_2$ unit-cell parameters), and an intrinsic (radiation-trapping-corrected) upper-state lifetime $\tau \approx 300 \mu\text{s}$, obtained by extrapolating fluorescence decay measurements to the low-concentration limit where reabsorption effects are minimized [22], Eq. (3.3) gives $P_{\text{transp}} \approx 68 \text{ mW}$, with $P_{\text{gain}}(T)$ ranging from 9 to 31 mW over the candidate output couplers.

3.4.3 Intracavity pulse energy and stability comparison

Table 3.1 summarizes, for the output-coupler transmissions available in the laboratory, the threshold pump power $P_{\text{th}}(T)$ from Eq. (3.3), the slope efficiency $\eta_s(T)$, the mode-locked output power $P_{\text{ML}}(T) = \eta_{\text{ML}} \eta_s(T) [P_{\text{pump}} - P_{\text{th}}(T)]$ with $P_{\text{pump}} = 400$ mW and $\eta_{\text{ML}} \approx 0.85$, the intracavity pulse energy $E_{\text{cav}}(T) = P_{\text{ML}}(T)/(f_{\text{rep}}T)$, and the critical energy $E_{\text{crit}}(T)$ from Section 1.6.

T_{OC}	P_{th}	η_s	P_{ML}	E_{cav}	E_{crit}
2.4%	77 mW	48.1%	132 mW	91.6 nJ	30.8 nJ
5%	84 mW	56.8%	152 mW	50.8 nJ	19.7 nJ
10%	99 mW	62.0%	159 mW	26.5 nJ	10.8 nJ

Table 3.1: Calculated threshold pump power, slope efficiency, mode-locked output power, intracavity pulse energy, and critical energy for the candidate output-coupler transmissions.

As shown in Table 3.1, $E_{\text{cav}}(T)$ exceeds $E_{\text{crit}}(T)$ for all three candidate output couplers, with a safety margin $E_{\text{cav}}/E_{\text{crit}}$ decreasing from approximately 3.0 at $T_{\text{OC}} = 2.4\%$ to approximately 2.5 at $T_{\text{OC}} = 10\%$. This preliminary theoretical analysis confirmed that stable, self-starting cw mode-locking was expected to be achievable for all the candidate output couplers without exposing the SESAM to excessive peak fluence, consistent with the stable mode-locking operation subsequently observed and discussed in Section 3.7.1.

3.5 Pump beam design

Once the resonator geometry had been defined, the pump delivery optics were designed in order to achieve an appropriate overlap between the pump beam and the intracavity laser mode inside the gain crystal.

The beam waist obtained from the ABCD analysis provided a reference for the design of the pumping system. In the selected resonator configuration, the laser mode radius inside the Yb crystal was approximately $17 \mu\text{m}$.

Rather than maximizing the pump area, the pump beam was intentionally designed to be slightly smaller than the intracavity laser mode. This approach introduces a

soft-aperture effect, since the optical gain is concentrated in the central region of the resonator mode. As a consequence, higher-order transverse modes experience reduced gain and are naturally suppressed, promoting stable operation in the fundamental transverse mode.

The pump optics were therefore designed to generate the desired spot size inside the crystal while maintaining efficient overlap with the resonator mode.

3.5.1 Pump beam polarization

Efficient pumping required a well-defined linear polarization state. However, the pump diode was delivered with a standard optical fiber rather than a polarization-maintaining fiber, resulting in an output polarization that was not intrinsically stable or well defined.

To obtain a preferential linear polarization, a simple polarization control technique based on fiber coiling was implemented. The output beam was analyzed using a linear polarizer aligned with the desired polarization direction on the optical table. While monitoring the transmitted power, controlled bends were introduced along the fiber pigtail and progressively adjusted in order to maximize the transmission through the polarizer.

The induced birefringence associated with the fiber bending modifies the polarization evolution along the propagation path, making it possible to preferentially align the output beam with the selected polarization axis. Using this approach, approximately 80% of the optical power was concentrated in the desired linear polarization state, providing a sufficiently polarized pump beam for the subsequent experiments.

3.5.2 Pump source characterization

The pump source consisted of a Single-Mode (SM) fiber-coupled laser diode operating at 976 *nm*. Although the nominal beam parameters were provided by the manufacturer, an experimental characterization of the beam emerging from the delivery fiber was carried out.

The aim of these measurements was not only to verify the specified performance, but also to determine the actual mode-field diameter (MFD) of the fiber output, which is a key parameter for the design of the pump imaging optics.

Since the fiber mode cannot be measured directly, a preliminary telescope was assembled to image the beam and reconstruct its waist through Gaussian beam propagation.

The preliminary optical system consisted of a collimating lens with focal length $f_1 = 15$ mm followed by a focusing lens with focal length $f_2 = 100$ mm, corresponding to a telescope magnification

$$k = \frac{f_2}{f_1} = 6.67.$$

The beam profile was measured scanning with the CCD camera along the focal plane of the pump telescope. A series of beam images were acquired at different positions along the propagation direction, allowing the evolution of the beam radius to be reconstructed experimentally. The experimental data were fitted using the Gaussian beam propagation model in order to determine the beam waist, waist position and beam quality factor.

$$W(z) = W_0 \sqrt{1 + \left(\frac{M^2 \lambda (z - z_0)}{\pi W_0^2} \right)^2}, \quad (3.4)$$

where W_0 is the beam waist radius, z_0 is the waist position, and M^2 is the beam quality factor. The fitting procedure yielded waist radii of

$$W_{0x} = 23.61 \text{ } \mu\text{m}, \quad W_{0y} = 24.45 \text{ } \mu\text{m},$$

The fitted beam quality factor was found to be approximately unity along both transverse directions, confirming the expected near diffraction-limited propagation of the single-mode pump beam.

Since the measured waist corresponds to the image produced by the preliminary telescope, the actual mode-field radius at the fiber output was obtained by accounting for the telescope magnification. Considering the telescope magnification

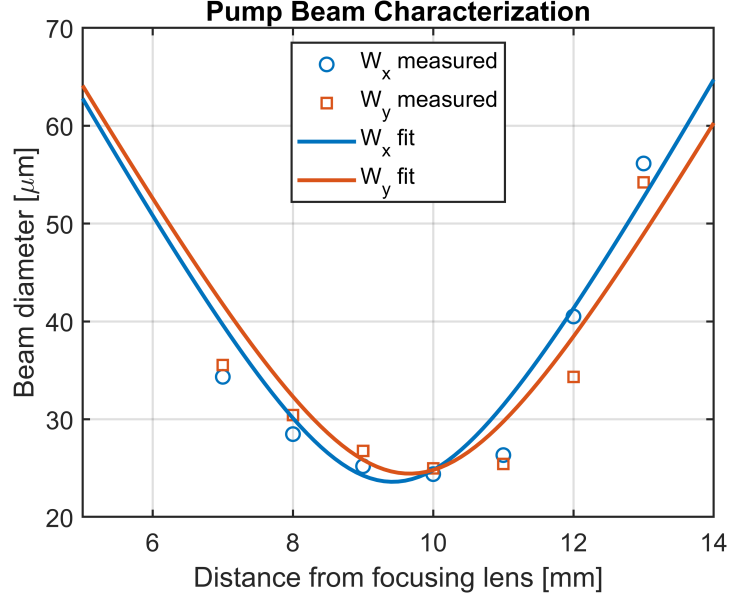


Figure 3.7: measured beam diameters together with the Gaussian beam fits used to extract the beam waist.

of $k = 6.67$, the reconstructed beam waist at the fiber output was found to be approximately $3.6 \mu\text{m}$, corresponding to a mode-field diameter of about $7.2 \mu\text{m}$. This value was subsequently used as the input parameter for the design and optimization of the final pump delivery optics presented in the following section.

3.5.3 Pump telescope design

The experimentally reconstructed fiber mode-field radius $\approx 3.6 \mu\text{m}$ was used to design the pump delivery optics and obtain the desired pump spot size inside the gain crystal.

A two-lens telescope configuration was adopted. The beam emerging from the delivery fiber was first collimated using a lens with focal length $f_1 = 30 \text{ mm}$. A second lens with focal length $f_2 = 150 \text{ mm}$ was then employed to focus the pump radiation into the Yb:KYW crystal.

The selected focal lengths provide a magnification factor

$$k = \frac{f_2}{f_1} = 5,$$

allowing the pump beam dimensions to be adjusted according to the requirements

identified from the cavity analysis. In particular, the telescope was designed to generate a pump spot slightly smaller than the intracavity laser mode, promoting fundamental transverse mode operation through the soft-aperture effect discussed previously.

A dichroic mirror was placed between the focusing lens and the gain crystal. The coating was designed to transmit the pump wavelength at 976 nm while reflecting the laser wavelength around 1040 nm. This element enabled the pump beam to be coupled into the crystal while simultaneously acting as one of the cavity folding mirrors.

The final optical arrangement adopted for the pump delivery system is shown in Fig. 3.8.

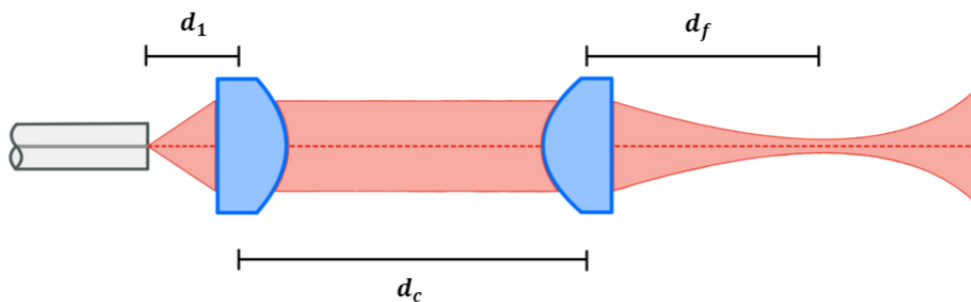


Figure 3.8: Pump delivery telescope used to focus the pump radiation into the Yb:KYW crystal. From left to right: single-mode delivery fiber, collimating lens ($f_1 = 30$ mm), focusing lens ($f_2 = 150$ mm). The corresponding optical distances are $d_1 = 30$ mm, $d_c = 135$ mm, and $d_f = 150$ mm.

3.6 Oscillator assembly and continuous-wave operation

Following the completion of the cavity and pump design, the oscillator was assembled on the optical table according to the geometry obtained from the numerical analysis.

Before attempting mode-locked operation, the resonator was initially configured

to operate in continuous-wave (CW) regime. This intermediate step allowed the cavity alignment, pump coupling, and laser performance to be evaluated independently of the mode-locking dynamics.

To this end, the SESAM was temporarily replaced by a high-reflectivity end mirror, enabling the resonator to operate as a conventional CW laser. The cavity included the Yb:KYW gain crystal, the curved mirrors M_1 and M_2 , the output coupler, and a set of GTI mirrors used as folding elements to realize the optical path length required by the design.

Although dispersion compensation is not required during CW operation, the GTI mirrors were already incorporated into the cavity because of their high reflectivity and compact implementation. This approach allowed the same cavity geometry to be preserved for the subsequent mode-locked configuration while maintaining a relatively small footprint on the optical table.

A dichroic mirror was placed immediately after mirror M_2 in order to remove the residual pump radiation that was not absorbed by the gain crystal. This prevented the unabsorbed pump light from propagating through the remaining cavity arm and enabled a cleaner characterization of the laser output.

The resulting experimental cavity layout is shown in Fig. 3.9.

All optics components of the layout are described in section 3.7.1.

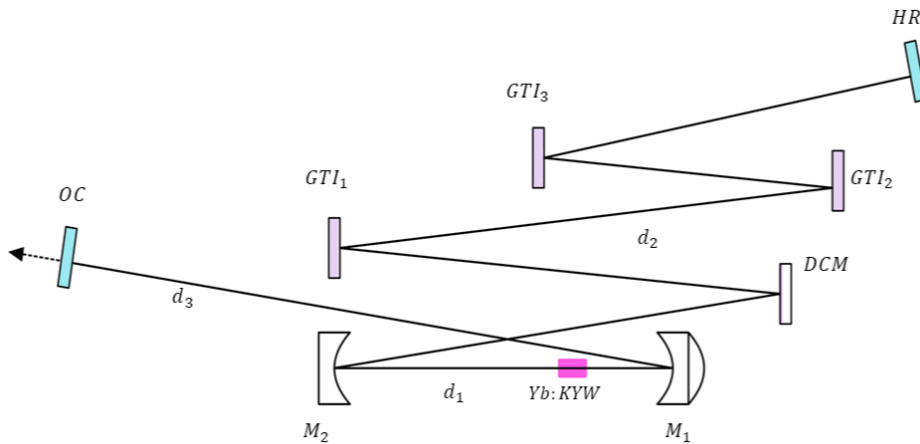


Figure 3.9: Continuous-wave X-folded layout with end mirror HR.

3.6.1 CW performance characterization

After achieving stable CW operation, the oscillator performance was characterized by measuring the output power as a function of the absorbed pump power.

The absorbed pump power was determined from the difference between the incident pump power at the crystal position and the residual pump power measured after the dichroic mirror used to reject the unabsorbed pump radiation.

Several output couplers were investigated in order to evaluate the extraction efficiency of the resonator and identify the most suitable configuration for subsequent mode-locked operation.

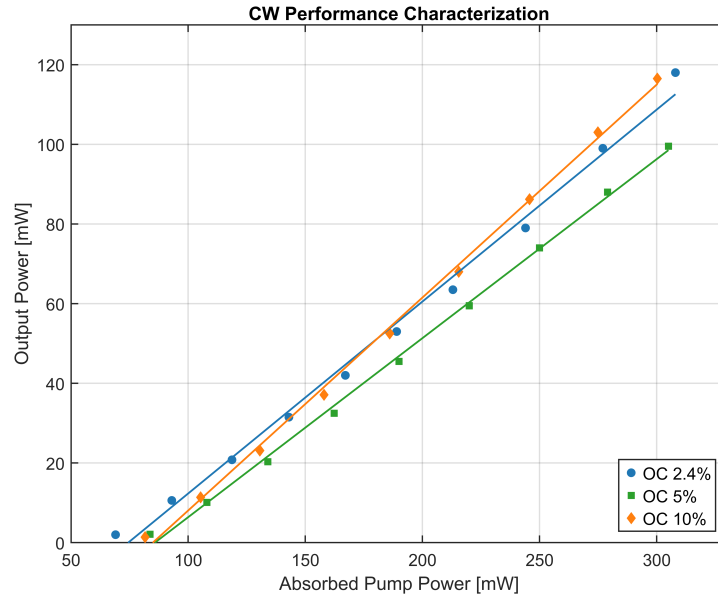


Figure 3.10: Continuous-wave output power versus absorbed pump power for different output coupler transmissions.

Figure 3.10 compares the CW output power obtained with output couplers of 2.4%, 5%, and 10% transmission. Linear fits of the experimental data yielded slope efficiencies of approximately 48.2%, 48.5%, and 53.5%, respectively.

Among the tested configurations, the 10% output coupler provided the highest extraction efficiency and was therefore selected for the subsequent mode-locking experiments.

3.7 Mode-locked operation

Following the CW characterization, the oscillator was configured for passive mode-locking by replacing the high-reflectivity end mirror with a SESAM. The aim was to achieve stable femtosecond pulse generation and to experimentally verify the design choices discussed in the previous sections. Once mode-locked operation had been established, the spectral and temporal characteristics of the generated pulses were measured and analyzed.

3.7.1 Mode-locking initiation

After completing the CW characterization, the high-reflectivity end mirror was removed and replaced by the SESAM, restoring the cavity configuration designed for passive mode-locking. A concave mirror was positioned immediately before the SESAM in order to focus the intracavity beam onto the absorber and achieve the fluence required for efficient saturable absorption.

Since the SESAM behaves as a highly reflective mirror at low intensities, the cavity could first be realigned to recover stable CW operation. Once lasing was re-established, the alignment of the resonator was progressively optimized while monitoring the output power. Maximizing the output power also corresponds to maximizing the intracavity circulating power, which increases the intensity incident on the SESAM and facilitates the onset of mode-locking.

During this procedure, the laser output was continuously monitored using both a power meter and an optical spectrum analyzer. The output power was optimized while observing the optical spectrum in order to identify the transition from CW operation to the mode-locked regime.

After fine adjustment of the cavity alignment, stable passive mode-locking was achieved. The oscillator produced soliton pulses centered at 1040 nm with vertical polarization with respect to the optical table (corresponding to the Np-axis direction) and an average output power of approximately 55–60 mW. The repetition frequency was approximately 60 MHz, in agreement with the value expected from the designed cavity length.

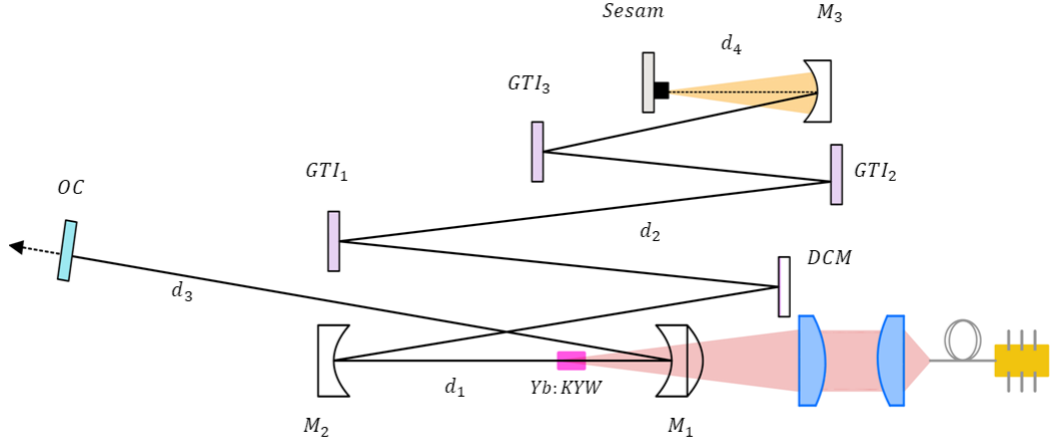


Figure 3.11: Experimental layout of the Yb:KYW resonator is composed of the curved mirrors M_1 ($R = 75$ mm), M_2 ($R = 150$ mm), and M_3 ($R = 300$ mm), the output coupler (OC), the SESAM, the dichroic mirror (DCM), and three GTI mirrors used for intracavity dispersion compensation. The cavity arm lengths are $d_1 = 113$ mm, $d_2 = 1490$ mm, $d_3 = 790$ mm, and $d_4 = 154$ mm.

3.7.2 Mode-locking optimization

Although stable passive mode-locking was readily achieved, the first operating configurations did not fully satisfy the requirements of the oscillator as a seed source for the subsequent GMN amplifier. The generated pulses were shorter than desired and exhibited a broader optical spectrum than required. Consequently, the resonator was optimized to obtain longer transform-limited pulses while preserving stable self-starting mode-locking.

To this end, different cavity configurations were experimentally investigated by varying both the output-coupler transmission and the intracavity GDD. Output couplers with transmission values of 2.5%, 5%, 10%, and 16% were tested during the optimization process. Figure 3.12 compares representative intensity autocorrelation traces obtained using the 5% and 10% output couplers.

According to the theory of temporal solitons, ultrashort pulse generation in a passively mode-locked laser operating in the soliton regime results from the balance between SPM and negative group-velocity dispersion (GVD). When these two effects exactly compensate each other, a fundamental soliton is formed, whose

peak intracavity intensity I_0 and pulse duration T_0 satisfy the relation [14]

$$I_0 T_0^2 = \frac{c|\beta_2|}{n_2 \omega}, \quad (3.5)$$

where β_2 is the group-velocity dispersion parameter, n_2 is the nonlinear refractive index, and ω is the optical angular frequency.

Rearranging Eq. 3.5 with respect to the pulse duration yields

$$T_0 = \sqrt{\frac{c|\beta_2|}{n_2 \omega I_0}}. \quad (3.6)$$

Equation 3.6 shows that, for a fixed intracavity dispersion, the pulse duration increases as the intracavity peak intensity decreases. Increasing the output-coupler transmission extracts a larger fraction of the circulating power from the cavity, thereby reducing the intracavity pulse intensity and promoting the generation of longer soliton pulses.

This trend is confirmed by the measurements reported in Fig. 3.12. Increasing the output-coupler transmission from 5% to 10% increases the pulse duration from approximately 152 fs to 242 fs while simultaneously narrowing the optical spectrum, in agreement with the Fourier relationship between pulse duration and spectral bandwidth.

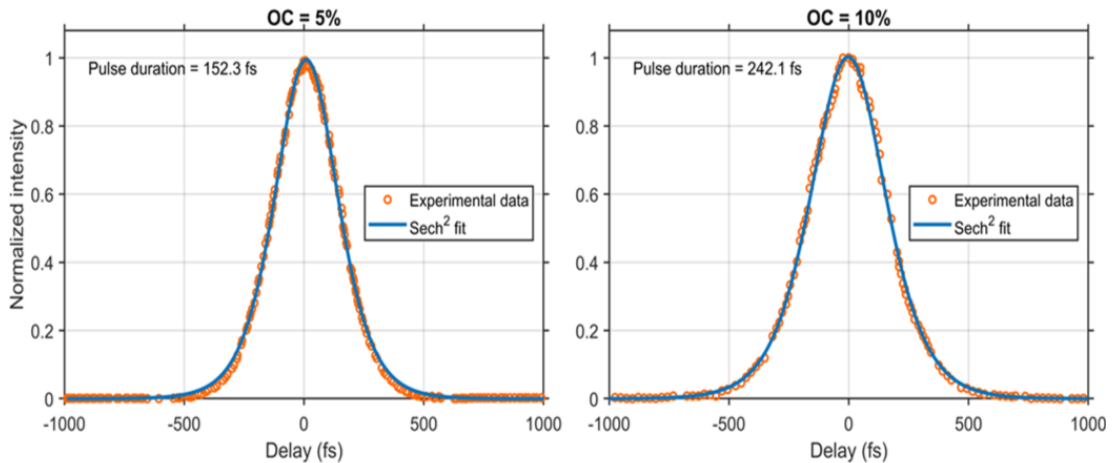


Figure 3.12: Comparison between the intensity autocorrelation traces measured using output couplers with transmission values of 5% and 10%.

Although an output coupler with 16% transmission further reduced the intracavity pulse intensity, the mode-locking regime became significantly less robust. In this configuration, the mode-locking threshold approached the maximum pump power available from the pump diode, making reliable self-starting mode-locking difficult to achieve. Consequently, the 10% output coupler represented the best compromise between pulse duration, mode-locking stability, and available pump power.

Once the optimal output coupler had been identified, further pulse lengthening could no longer be achieved by reducing the intracavity pulse intensity without compromising the stability of the laser. The remaining degree of freedom was therefore the intracavity dispersion. According to Eq. 3.5, increasing the magnitude of the negative group-velocity dispersion while maintaining approximately the same intracavity pulse intensity results in longer soliton pulses. The initial cavity configuration employed one dispersion-compensating mirror providing -375 fs^2 of group-delay dispersion together with two mirrors providing approximately -550 fs^2 each. Several dispersion-compensation configurations were investigated by replacing these mirrors with elements providing different values of group-delay dispersion. The final cavity configuration employed one dispersion-compensating mirror providing approximately -1200 fs^2 together with two additional mirrors providing approximately -550 fs^2 each. This configuration provided the best compromise between pulse duration, spectral bandwidth, and long-term mode-locking stability, yielding the final operating conditions discussed in the following sections.

3.7.3 Spectral and temporal characterization

The optical spectrum of the optimized mode-locked oscillator was measured using an optical spectrum analyzer and is reported in Fig. 3.13.

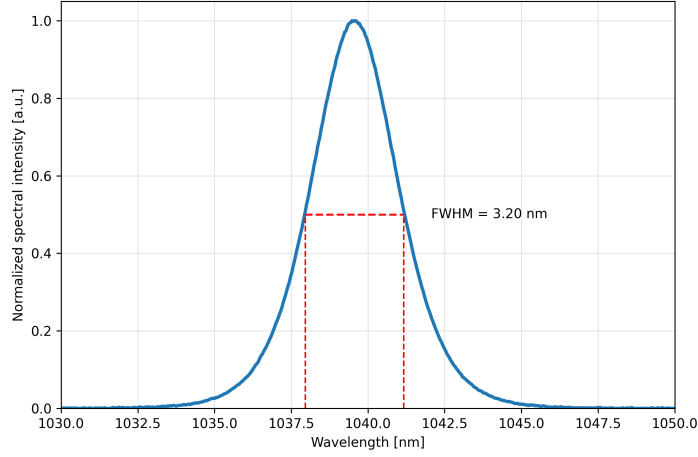


Figure 3.13: Normalized optical spectrum, centered at approximately 1040 nm with a full width at half maximum (FWHM) bandwidth of 3.2 nm.

As discussed in the previous section, the measured spectrum appears relatively narrow compared with that typically obtained from femtosecond mode-locked oscillators. This was, however, an intentional design choice. Since the oscillator was specifically developed as the seed source for a subsequent GMNA layout, a broad seed spectrum was neither required nor desirable, as it could complicate the nonlinear pulse evolution inside the amplifier. The intracavity dispersion was therefore optimized to obtain a stable soliton regime with a comparatively narrow spectral bandwidth. The measured autocorrelation trace is shown in Fig. 3.14.

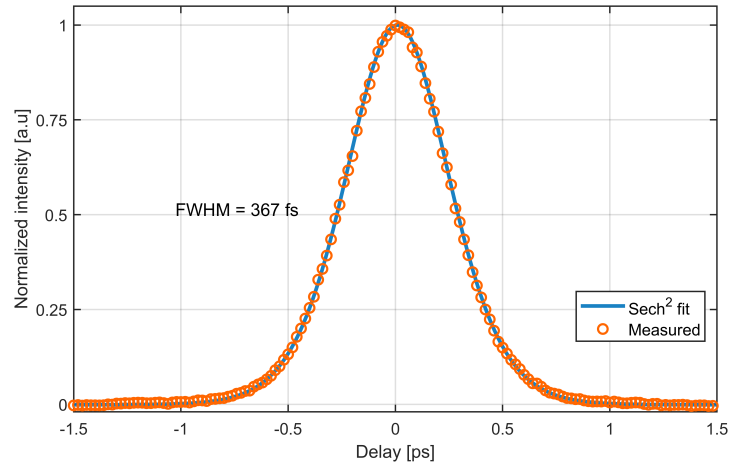


Figure 3.14: Normalized intensity autocorrelation trace with the corresponding sech^2 fit.

Assuming a sech^2 pulse profile, the measured autocorrelation trace yields a pulse

duration of approximately $\Delta\tau_p \approx 367$ fs.

As discussed by Svelto [23], the pulse duration and the spectral bandwidth of a mode-locked laser are related through the Fourier-transform relationship between the temporal and spectral representations of the optical field. The pulse duration and the spectral bandwidth are related by

$$\Delta\tau_p = \frac{\beta}{\Delta\nu},$$

where $\Delta\nu$ is the optical bandwidth expressed in frequency units and β is a numerical factor that depends on the pulse shape.

The optical bandwidth measured by the optical spectrum analyzer is expressed in wavelength units and can be converted to frequency units through

$$\Delta\nu \simeq \frac{c}{\lambda_0^2} \Delta\lambda,$$

where c is the speed of light and λ_0 is the central wavelength.

For transform-limited sech^2 pulses, the corresponding time-bandwidth product (TBP) is

$$\Delta\nu \Delta\tau_p = 0.315. \tag{3.7}$$

Using the measured spectral bandwidth of 3.2 nm and the pulse duration extracted from the autocorrelation measurement, the time-bandwidth product was found to be

$$TBP = 0.326$$

This value is in excellent agreement with the transform-limited value of 0.315 expected for sech^2 pulses, differing by less than 4%.

The close agreement between the measured and theoretical time-bandwidth products indicates that the generated pulses were nearly Fourier-limited with only a small residual chirp, confirming stable soliton mode-locking in the designed oscillator.

The measured pulse characteristics demonstrate stable operation of the oscillator and are summarized in Table 3.2.

Parameter	Value
Central wavelength, λ_0	1040 nm
Spectral bandwidth, $\Delta\lambda$	3.2 nm
Pulse duration, $\Delta\tau_p$	367 fs
Repetition rate, f_{rep}	60 MHz
Average output power, P_{out}	60 mW
Output pulse energy, E_{out}	1.0 nJ
Intracavity pulse energy, E_{cav}	10 nJ

Table 3.2: Summary of the main parameters of the mode-locked Yb:KYW oscillator.

4 Gain Managed Non-linear Amplification

Following the successful realization and characterization of the SESAM mode-locked Yb:KYW oscillator, the next stage of the experimental work consisted of the implementation of the amplification system. Once stable mode-locked operation had been achieved and all the relevant operating parameters had been optimized, the oscillator was employed as the seed source for the fiber amplifier, which was operated in the GMNA regime, introduced in Chapter 2.

The objective of this stage was to increase the pulse energy while preserving the pulse characteristics required for subsequent pulse compression. As discussed in the theoretical overview, the selected amplification architecture was based on the GMNA technique, which offers a relatively simple and compact implementation compared to more conventional ultrafast amplification schemes.

4.1 Amplifier implementation

From an experimental perspective, the realization of the amplifier required coupling both the seed pulses generated by the oscillator and the pump radiation into the ytterbium-doped active fiber.

Two different experimental approaches were considered for accomplishing this task.

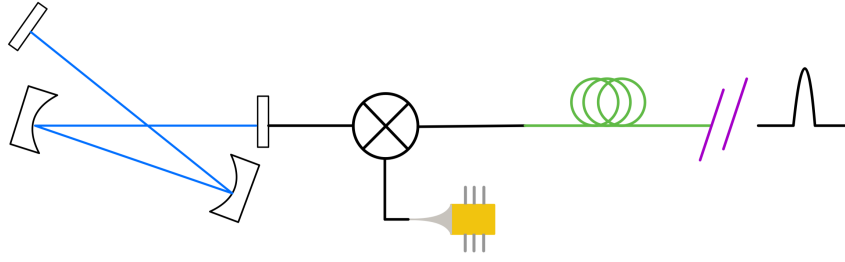


Figure 4.1: Schematic view of amplification system.

4.1.1 Fiber-integrated configuration

The first approach relied on a fully fiber-integrated architecture. In this configuration, the oscillator output is coupled into a passive fiber through a micro-collimator and subsequently combined with the pump radiation using a fused pump combiner. The signal and pump beams are therefore launched into the active fiber through an entirely fiber-based optical path.

This solution represents the preferred choice for industrial laser systems, as it provides excellent mechanical stability, high coupling efficiency, and alignment-free operation after assembly. Moreover, the absence of free-space optics significantly improves the robustness and long-term reliability of the amplification stage.

In the laboratory setup, however, this configuration presented several practical limitations. The passive fiber sections preceding the active fiber introduce an additional propagation length, allowing nonlinear effects, such as self-phase modulation, to modify the seed pulses before amplification takes place. As discussed in Chapter 2, this undesired nonlinear evolution may lead to pulse stretching and consequently reduce the efficiency of the amplification process.

Although these passive fiber sections could in principle be shortened by cutting and resplicing the fibers, such a solution is generally unsuitable in a research laboratory, where the same optical components are frequently reused in different experimental configurations. Permanent modifications of commercially available fiber components would considerably reduce their flexibility for future experiments.

4.1.2 Free-space implementation

For these reasons, the amplifier was initially implemented using a free-space coupling configuration. In this approach, the seed beam generated by the oscillator and the pump beam were independently collimated and spatially overlapped in free space before being focused directly into the active fiber.

Although this configuration requires a significantly more demanding optical alignment procedure, it eliminates the passive-fiber propagation preceding the active fiber, thereby preventing unwanted nonlinear pulse evolution before amplification. Furthermore, all optical components can be reused without permanent modifications, making this configuration particularly suitable for laboratory investigations and for the optimization of the amplifier architecture.

The optical layout of the implemented amplification stage is described in the following sections.

4.2 Experimental optical setup

The experimental optical layout adopted for the implementation of the gain-managed nonlinear amplifier is shown in Figure 4.2. The setup can be divided into three functional stages: the seed delivery stage, the pump delivery stage, and the coupling stage, where both beams are spatially overlapped and simultaneously injected into the ytterbium-doped active fiber. This modular organization simplifies the description of the optical architecture while highlighting the role of each subsystem.

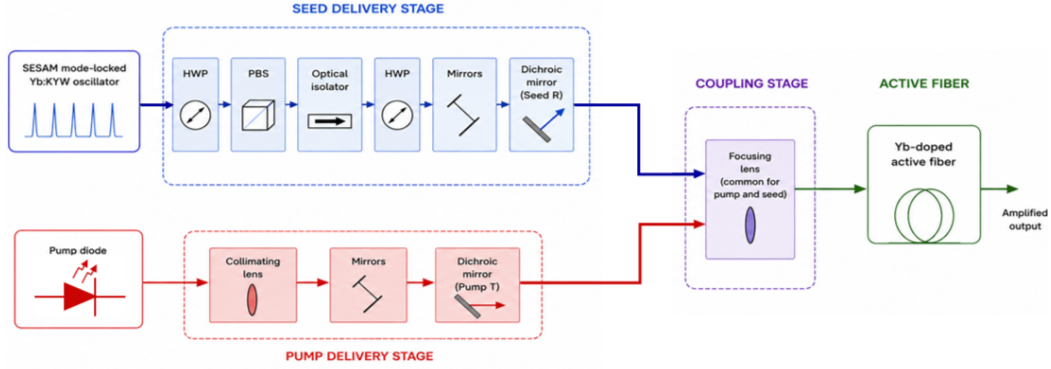


Figure 4.2: Experimental optical layout of the free-space GMNA amplifier.

Seed delivery stage The seed beam was routed from the SESAM mode-locked Yb:KYW oscillator toward the coupling stage. A half-wave plate (HWP) and a polarizing beam splitter (PBS) were used to control the power injected into the amplifier. The PBS also acted as the input polarizer for a Faraday rotator we employed to set up a Faraday isolator that protected the oscillator from optical feedback. As with any real optical isolator, the device does not provide unitary transmission: insertion losses associated with the polarizers and the Faraday rotator itself result in a transmission efficiency of approximately 90%, which was considered when evaluating the power available for amplification. After the isolator, a second HWP set the polarization for coupling into the active fiber. Two steering mirrors directed the beam toward the dichroic mirror, which reflected the seed radiation toward the $f_2 = 12$ mm achromatic lens that was used to couple both the pump and the seed beams into the active fiber of the amplifier.

Pump delivery stage The pump radiation was delivered by a fiber-coupled laser diode with a maximum output power of 9 W operated up to 10 A to avoid excessive thermal stress on the diode, which was actively fan-cooled during operation. The diode emitted at 976 nm stabilized by a fiber Bragg grating (FBG) and was delivered through a mono-mode fiber with a core diameter of $105\ \mu\text{m}$ and a numerical aperture of $\text{NA} = 0.22$. The beam emerging from the pigtailed fiber was

collimated with an $f_1 = 12$ mm achromatic lens, identical to the one used to focus the pump radiation into the double-clad active fiber, and redirected by two high-reflectivity mirrors toward the dichroic mirror. The dichroic mirror transmitted the pump radiation and reflected the seed beam, allowing the two beams to be spatially overlapped before the focusing lens. The use of a single focusing optic ensured that both radiations were focused onto the same region of the fiber input facet, resulting in a compact free-space coupling scheme. The alignment procedure adopted to maximize the pump coupling efficiency and optimize the spatial overlap between the two beams is described in the following section.

4.3 Alignment procedure

The optical paths were aligned sequentially, starting with the pump beam and subsequently introducing the seed beam into the already optimized coupling configuration. This approach allowed the two paths to be adjusted independently before their simultaneous injection into the active fiber. The following subsections describe the experimental steps adopted for the pump coupling, seed alignment, and final optimization of the amplifier.

4.3.1 Pump coupling

The pump path was aligned first. The fiber-coupled pump diode was mounted on a fiber holder and followed by a collimating lens with a focal length of $f_1 = 12$ mm. The collimating lens was mounted on a dedicated translation stage, allowing precise longitudinal adjustment of its position. The collimated pump beam was then redirected by a pair of high-reflectivity mirrors operated at an incidence angle of 45° .

The first step consisted of positioning and approximately aligning these three components. The collimation of the pump beam was verified by observing the beam propagation over a relatively long distance. The two-mirror configuration provided the necessary degrees of freedom to adjust the beam direction and maintain a constant propagation height, while the 45° arrangement allowed the

optical path to be conveniently folded and kept compact on the optical table. The hole pattern of the table was used as a geometrical reference, and the beam height was matched to that of the seed beam, whose vertical position could not be adjusted.

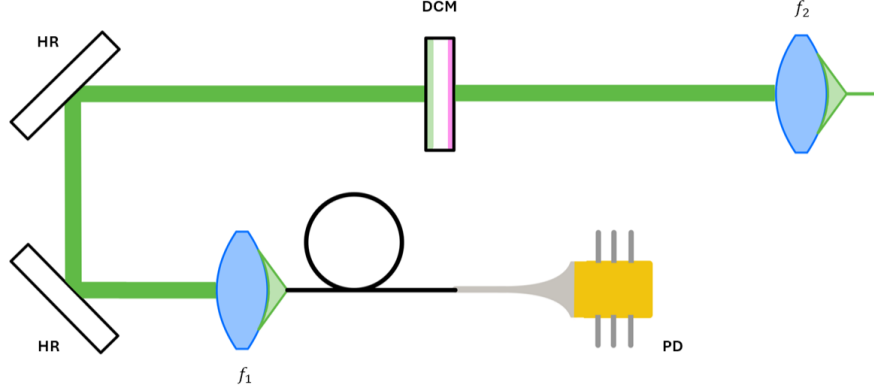


Figure 4.3: Optical setup for pump beam collimation, redirection, and focusing into the active fiber. The beam from the fiber-coupled pump diode (PD) is collimated by lens f_1 , redirected by two HR mirrors, combined with the seed at the dichroic mirror (DCM), and focused into the fiber by lens f_2 .

Once the pump beam was correctly aligned, the dichroic mirror and the focusing lens were introduced into the optical path. The focusing lens had a focal length of $f_2 = 12$ mm and was mounted on a dedicated translation stage to allow precise positioning along the propagation direction. We chose $f_1 = f_2$ to have a unitary telescope magnification since the diameter and numerical aperture of the pump diode fiber and double-clad amplifier fiber were the same.

The final coupling into the active fiber was performed using a visible green laser pointer as an alignment reference. The pointer beam was coupled in the opposite end of the active fiber, providing a visible reference of the pointing direction for a correct fiber coupling of the invisible pump and signal beams. The pump beam was then adjusted to overlap with this reference using the angular adjustments of the high-reflectivity mirror mounts and the translational degrees of freedom of the collimating and focusing lenses. Beam cards were used during this procedure to verify the approximate spatial alignment of the pump and reference beams.

Once the beams were sufficiently aligned, the reference laser was removed, and the optimization was continued using the pump beam itself. A useful feedback signal was provided by the active fiber, which exhibited visible green fluorescence when the pump radiation was successfully coupled into its core. The appearance of this fluorescence indicated that the pump radiation was effectively launched into the active fiber.

A power meter was subsequently positioned at the output of the active fiber. The available angular and translational degrees of freedom were then adjusted to maximize the transmitted pump power. This procedure provided the final optimization of the pump coupling and established the alignment conditions required for the subsequent seed injection into the active fiber.

4.3.2 Seed alignment

The optical path for the seed beam from the output coupler of the Yb:KYW oscillator toward the fiber amplifier is shown in Fig. 4.4. Before entering the isolator stage, a two-lens telescope, consisting of a focusing lens with focal length $f_{1a} = 20$ mm and a collimating lens with focal length $f_{2a} = 50$ mm separated by 70 mm, was used to expand the seed beam waist in order to have the correct beam diameter on the $f = 12$ mm focusing lens that was used to couple the pump in the active fiber cladding and the signal in the active fiber core.

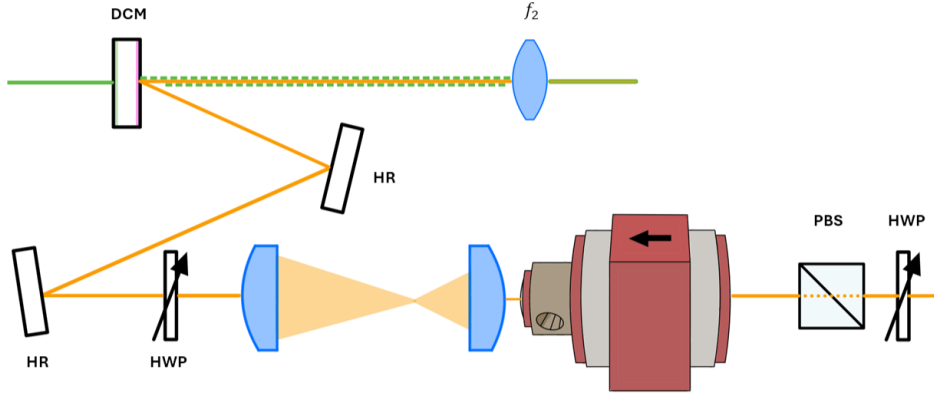


Figure 4.4: Optical setup for seed beam redirection and focusing into the active fiber. The seed passes through a half-wave plate (HWP), a polarizing beam splitter (PBS), a Faraday isolator, and a second HWP for polarization control, before being redirected by two HR mirrors to the dichroic mirror (DCM). The DCM reflects the seed and transmits the pump (green dashed line) toward the shared focusing lens f_2 .

4.3.3 Amplifier optimization

At this stage, the pump alignment obtained in the previous subsection was kept fixed and used as the reference for the seed coupling. The first goal was to verify that the seed beam was correctly coupled into the core of the active fiber. The output power from the active fiber was monitored together with the visible fluorescence generated by the pumped fiber. When the seed beam was progressively aligned with the fiber core, a marked reduction in the fluorescence intensity was observed, providing a direct qualitative indication that the seed radiation was being coupled into the guided mode of the active fiber and was progressively depleting population inversion, thus reducing the visible fluorescence.

Once seed coupling had been established, the angular and translational degrees of freedom available on the seed path were adjusted to maximize the output power while keeping the pump alignment unchanged. After reaching a local maximum, the pump alignment was slightly readjusted, and the seed alignment was optimized again. This iterative procedure was repeated by alternating between the pump and seed paths, progressively refining their spatial overlap and coupling conditions. The final optimization was continued until no significant improvement in the

output power could be obtained through further adjustments, defining the practical coupling limit achievable with the adopted free-space alignment procedure.

4.4 Experimental verification of the GMNA regime

Once the amplifier had been aligned and the seed and pump beams were successfully coupled into the active fiber, the next step was to verify experimentally that the system exhibited the characteristic behavior expected from a GMN amplifier. Since the GMNA process combines optical amplification with nonlinear spectral broadening, the verification was based on the joint monitoring of the output power and the evolution of the optical spectrum as a function of the pump power. These measurements were performed using a power meter and an optical spectrum analyzer, respectively.

4.4.1 Output power and spectral broadening

The first indication of successful amplification was obtained by monitoring the optical power at the output of the active fiber while progressively increasing the pump diode current. An increase in the pump current, and consequently in the available pump power, was expected to produce a corresponding increase in the amplified signal power.

In a GMNA system, this increase in pulse power during propagation through the active fiber simultaneously enhances the nonlinear phase accumulation associated with SPM, resulting in spectral broadening of the seed pulse. The output power and the optical spectrum were therefore recorded together for increasing pump power to directly correlate the amplifier gain behavior with the corresponding spectral evolution.

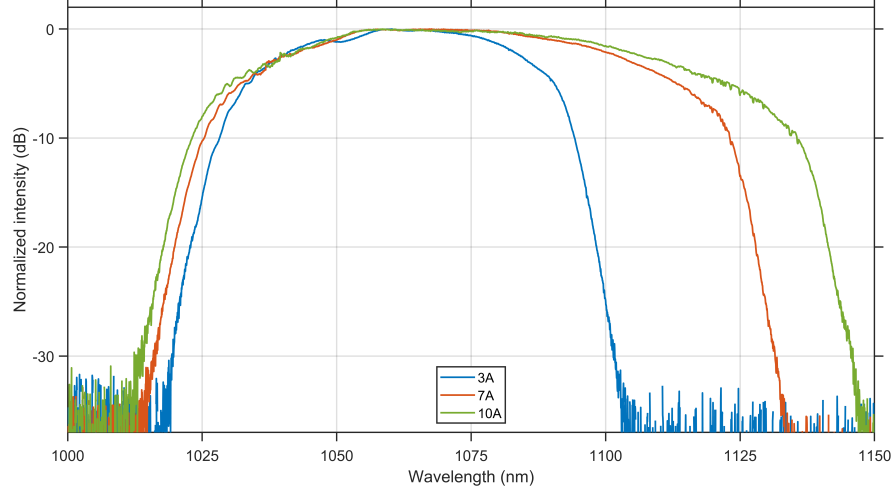


Figure 4.5: Optical spectra at the output of the active fiber for increasing pump diode current, showing the progressive spectral broadening with a relatively flat peak in log scale and a markedly asymmetric broadening towards the longer wavelengths, which is a fingerprint of the GMNA process.

Pump current	Output power	Bandwidth FWHM	Pulse energy
3 A	1.0 W	48 nm	16.7 nJ
7 A	2.9 W	66 nm	48.3 nJ
10 A	4.2 W	73 nm	70.0 nJ

Table 4.1: Output power, spectral bandwidth, and pulse energy were measured at increasing pump current.

Figure 4.5 shows the optical spectra recorded at the output of the active fiber for increasing pump power. For comparison, the oscillator provided a seed pulse with an optical bandwidth of approximately 3.2 nm and an average output power of 60 mW of which approximately 76% (≈ 45.6 mW) were effectively coupled into the amplifier, accounting for the transmission of the half-wave plates (98% each), the polarizing beam splitter (90%), and the Faraday isolator (88%). A progressive increase in the spectral bandwidth was observed as the pump power was raised, confirming the nonlinear spectral broadening expected from the GMNA process. In addition to the increase in bandwidth, the amplified spectra exhibited the characteristic broad and smooth spectral envelope associated with GMNA operation. The corresponding output power values are summarized in Table 4.1,

confirming that the spectral broadening occurred concurrently with the expected increase in amplified signal power.

To further characterize the power scaling behavior of the amplifier, the extraction efficiency was evaluated as

$$\eta_{\text{extraction}} = \frac{P_{\text{out}} - P_{\text{sig}}}{P_{\text{inc}}}, \quad (4.1)$$

where $P_{\text{sig}} \approx 45.7$ mW is the seed power effectively coupled into the active fiber and P_{inc} is the incident pump power. Figure 4.6 shows both the output power and the extraction efficiency as a function of incident pump power, with the corresponding pump current indicated on the top axis. While the output power increases essentially linearly with incident pump power over the entire investigated range, the extraction efficiency rises rapidly at low pump power and then saturates, reaching approximately 50% for pump currents at and above 8 A. This saturating behavior indicates that the amplifier was operating close to its maximum achievable extraction efficiency over most of the investigated range, rather than being limited by an insufficient pump power or an incompletely saturated gain.

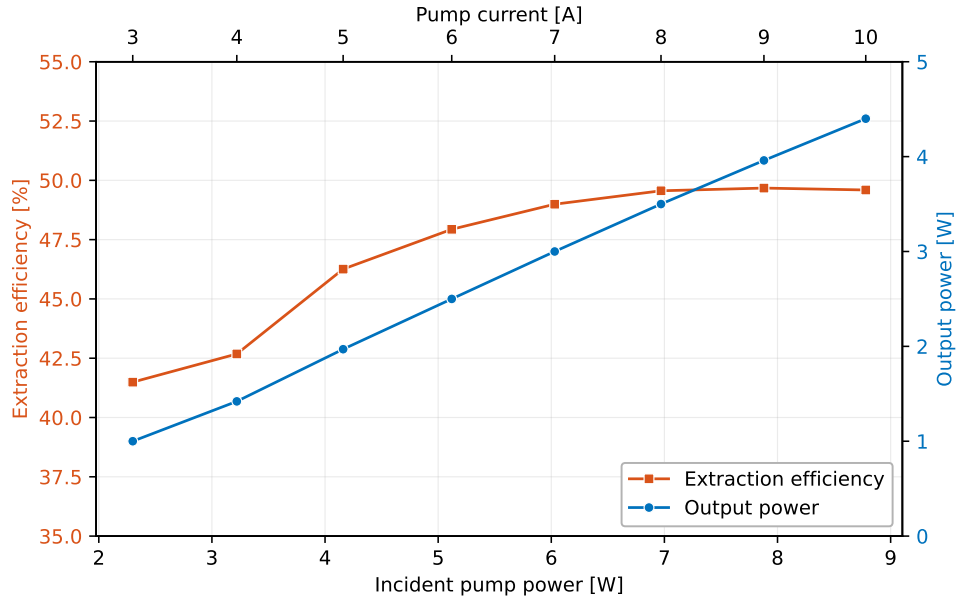


Figure 4.6: Output power (right axis) and extraction efficiency (left axis) as a function of incident pump power, with the corresponding pump current indicated on the top axis.

As described in Section 4.5.1, the output power and spectral measurements were performed after the Faraday isolator. The isolator has a transmission efficiency of approximately 90%, while additional power differences regarding the generated intracavity or in-fiber signal arise from the coupling conditions and from the overall losses and gain of the amplifier system. Therefore, the reported output powers represent the power available at the output measurement plane rather than the power directly generated within the active fiber.

The obtained output power and spectral broadening were sufficient to proceed to the subsequent pulse-compression stage.

4.5 Pulse compression

The spectral broadening observed at the output of the GMNA stage provided the broad optical bandwidth required for subsequent pulse compression. As discussed in Chapter 2, in the gain-managed nonlinear amplification regime, the gain and the nonlinear phase accumulation are not independent processes but evolve together along the active fiber: as the pulse energy increases due to amplification, the growing peak power simultaneously enhances SPM, progressively broadening the optical spectrum. The amplification stage, therefore, provides both the energy scaling and the spectral broadening required for the generation of shorter pulses after compression.

However, the amplified pulse cannot be directly regarded as a shorter pulse simply because of its increased spectral bandwidth. During propagation through the active fiber, the pulse also experiences group-velocity dispersion, resulting in an accumulated GDD and a modification of the temporal and spectral phase. The amplified pulse, therefore, exits the fiber with a significant chirp and is not generally transform-limited. A dispersive stage introducing a negative GDD is consequently required to remove the residual chirp and compress the pulse to the minimum possible duration.

Since a relatively large amount of negative dispersion is required to compensate for the accumulated dispersion of the amplifier, a diffraction-grating compressor was

employed. Grating pairs can provide substantial amounts of negative group-delay dispersion by spatially separating the different spectral components of the pulse and introducing a wavelength-dependent optical path [20]. By properly adjusting the geometry of the compressor, the dispersion introduced by the gratings can be used to compensate for the chirp accumulated in the active fiber.

The following subsections describe the optical configuration of the grating compressor, the procedure adopted to optimize the compression, and the temporal characterization of the resulting compressed pulses.

4.5.1 Output beam conditioning

Before entering the grating compressor, the amplified beam was prepared and routed through a dedicated free-space optical path. The radiation emerging from the active fiber was first collimated using a lens with a focal length of $f = 13$ mm. The expected collimated beam waist was estimated from a beam-quality measurement of the active fiber output mode ($M^2 = 1.1$, mode radius $w_0 = 5.6$ μm), via

$$W_{\text{collimated}} = \frac{M^2 \lambda f}{\pi w_0} \approx 845 \text{ } \mu\text{m}. \quad (4.2)$$

This estimation was confirmed by direct knife-edge measurements of the collimated beam. A beam radius $w_1 = 890$ μm was measured close to the collimating lens. A Faraday isolator was then introduced to prevent optical feedback and back reflections from the compressor from propagating toward the active fiber and the oscillator. After the isolator, a half-wave plate was used to adjust the linear polarization of the amplified beam to maximize the transmission through the optical components of the subsequent compression stage.

The beam was then redirected toward the grating compressor using a silver-coated mirror. Silver coatings provide a broad and uniform reflectance band extending from the visible to the mid-infrared, making them well suited for femtosecond pulsed applications where preserving the spectral integrity of the broadened pulse across its entire bandwidth is required.

4.5.2 Grating compressor implementation and compression procedure

The grating compressor was implemented in a double-pass configuration using two transmission diffraction gratings, as described in Section 2.5.2. After the silver-coated steering mirror described in the previous subsection, the amplified beam was first aligned to obtain a well-defined and straight propagation path. The beam height and horizontal position were adjusted using the hole pattern of the optical table as a geometrical reference.

A power meter was positioned on the reference propagation axis to monitor the beam power before the gratings. The first diffraction grating was then introduced into the beam path and positioned at the required incidence angle that maximizes the grating transmission (minimum deviation angle). Its tilt was adjusted while keeping the power meter fixed, such that the directly transmitted, zero-order component was reduced to nearly zero and the first-order diffracted beam was redirected toward the desired propagation direction. The second diffraction grating was subsequently positioned along this new propagation path and adjusted to receive the first-order diffracted beam. The second grating was positioned at the same incidence angle as the first one (hence, the two are perfectly parallel). Its orientation and position were adjusted so that the diffracted beam was redirected toward the original propagation path and reached the same spatial region used for the power measurement before the gratings. This procedure allowed the two gratings to be aligned regarding each other while preserving the reference optical axis.

After the two gratings had been aligned, a right-angle prism acting as a 180° retroreflector was introduced to redirect the beam back toward the grating pair while changing its vertical propagation level. The reflected beam, therefore, propagated through the two gratings a second time, undergoing a second contribution to the negative dispersion introduced by the grating pair. This double-pass configuration increased the total accumulated dispersion while maintaining a compact optical layout and, more importantly, allowed the different spectral components

to be spatially overlapped again that were initially laterally dispersed by the first grating.

The second grating and the right-angle prism were mounted on a common micrometric translation stage, allowing the grating separation to be finely adjusted while preserving the alignment obtained in the previous step. For the adopted compressor geometry, the group-delay dispersion introduced by the grating pair depends on the physical separation between the gratings. The grating separation was therefore varied continuously to adjust the amount of negative dispersion and to optimize the compensation of the chirp accumulated during propagation through the active fiber, as discussed in Section 4.5.3.

After the second passage through the gratings, the compressed beam was redirected by a second silver-coated mirror toward the output path, where the pulse power and temporal characteristics could be measured.

4.5.3 Compressed pulse characterization

After the spectral broadening generated in the GMNA stage and the subsequent compression by the double-pass grating compressor, the output pulses were characterized in the temporal domain. Since the pulse duration is on the femtosecond timescale and cannot be directly resolved by conventional photodetectors, an intensity autocorrelation measurement was employed.

$$A^{(2)}(\tau) = \int_{-\infty}^{+\infty} I(t) I(t - \tau) dt \quad (4.3)$$

The compressed pulses were characterized using a commercial autocorrelator (pulseCheck autocorrelator from APE). The instrument was connected to a dedicated acquisition and analysis software package, which was used to record the autocorrelation traces and perform the corresponding fits.

The measurements were repeated for the different amplification conditions investigated. Figure 4.7 shows the resulting autocorrelation traces for two of the pump-power conditions investigated, together with the corresponding sech^2 fits, yielding compressed pulse durations of 40.8 fs at 7 A and 37.8 fs at 10 A. Although

there is no specific physical justification for assuming a sech^2 temporal profile for the compressed pulse – unlike the seed pulse discussed in Section 1.4, the amplified pulse no longer propagates in the anomalous-dispersion, soliton-supporting regime, having instead undergone extensive nonlinear reshaping in the normal-dispersion active fiber (Section 2.4) – the sech^2 function is a standard empirical choice for characterizing compressed ultrashort pulses, and the fit remains reasonably accurate over the main lobe of the autocorrelation trace. The goodness of this empirical fit is quantified by the acquisition software through a pulse quality parameter, defined as the ratio between the area under the fitted sech^2 curve and the area under the measured autocorrelation trace, with a maximum value of unity corresponding to a perfect match between the two. The pulses shown in Fig. 4.7 exhibit a pulse quality of 0.93 at 7 A and 0.90 at 10 A values this close to unity confirm that the sech^2 approximation describes the main compressed peak well, with only a comparatively small fraction of the pulse energy departing from this ideal shape.

The residual deviation from unity pulse quality originates from a low-intensity pedestal surrounding the main compressed peak, clearly visible in the wings of the autocorrelation traces in Fig. 4.7. This pedestal is a well-known consequence of nonlinear pulse amplification: while the double-pass grating compressor efficiently compensates for the dominant, quasi-linear chirp accumulated in the active fiber, it is primarily designed to provide a nearly constant, wavelength-independent GDD (Eq. (2.4)) and cannot fully compensate for residual higher-order spectral phase terms. These residual terms become increasingly significant as the amplified spectrum is broadened further from the seed bandwidth, since the nonlinear phase accumulated through self-phase modulation is not perfectly quadratic in frequency across the full amplified bandwidth. The spectral components affected by this residual phase are not fully recompressed into the main pulse and instead contribute to the low-intensity pedestal noticed in the autocorrelation wings, consistent with similar observations reported for other GMNA systems [4].

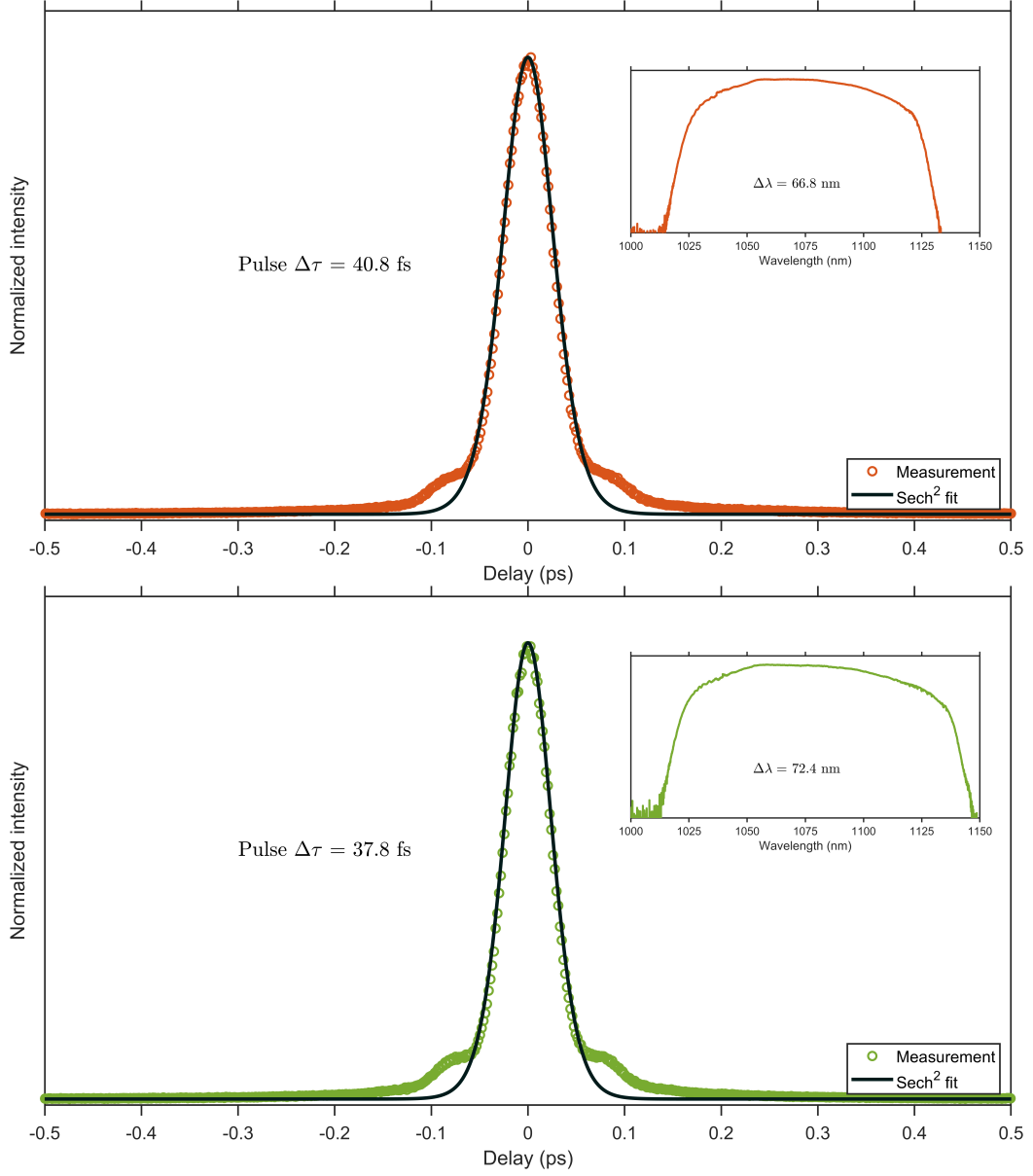


Figure 4.7: Intensity autocorrelation traces of the compressed pulses at pump diode currents of 7 A (orange) and 10 A (green), with the corresponding sech^2 fits.

To further validate the compressed pulse characterization, a FROG measurement [24] of the compressed pulse was performed at the maximum pump power. Figure 4.8 shows the experimental (binned) and retrieved SHG-FROG traces, which are in close visual agreement, confirming the reliability of the retrieval.

From the retrieved complex field, both the temporal intensity profile and the spectral amplitude, together with their respective retrieved phases, were extracted

(Fig. 4.9). The retrieved spectral amplitude closely follows the independently measured OSA spectrum at the same pump current, providing a cross-check between the two acquisition methods. Within the main lobe of the pulse, the retrieved temporal phase remains essentially flat, confirming that the grating pair is providing a good compensation of GVD for the pulse, allowing a pulse compression that should be close to the Fourier-transform limit.

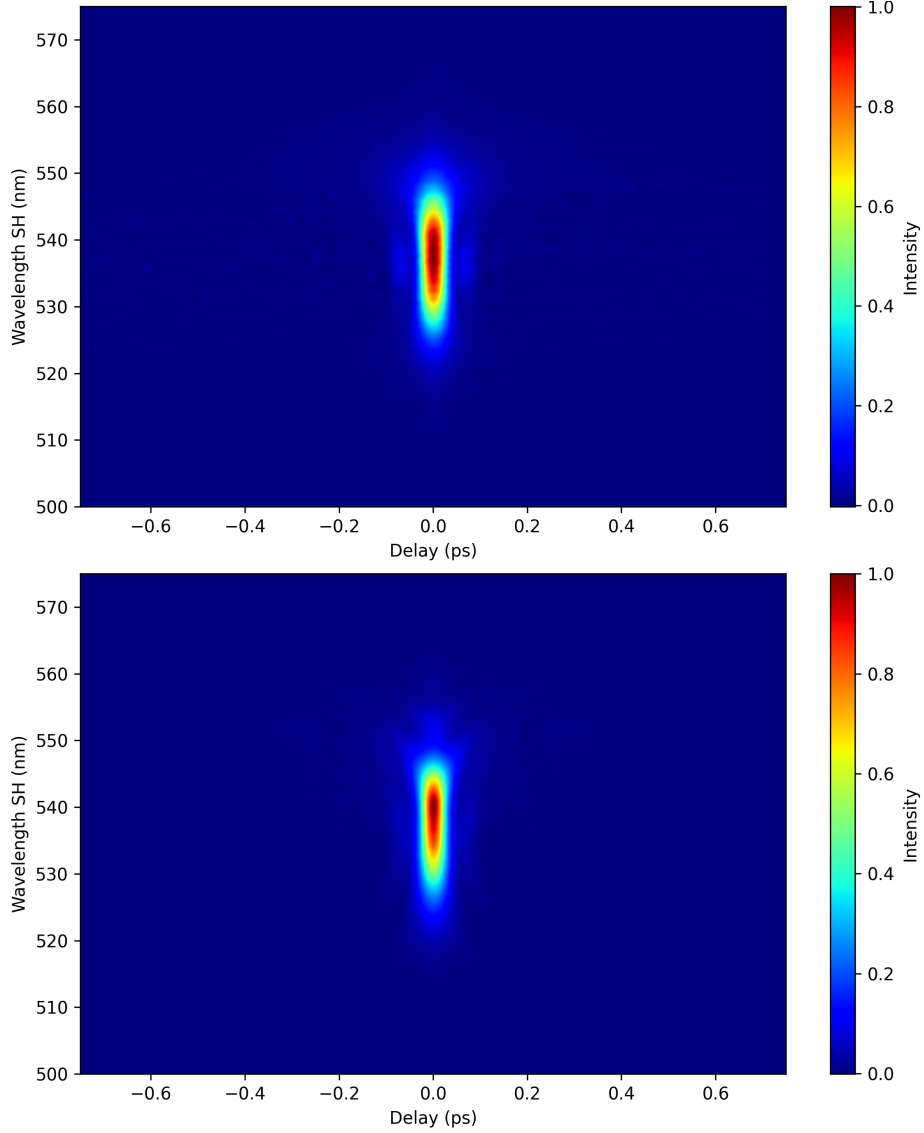


Figure 4.8: Experimental (top) and retrieved (bottom) SHG-FROG traces of the compressed pulse at 10 A pump current.

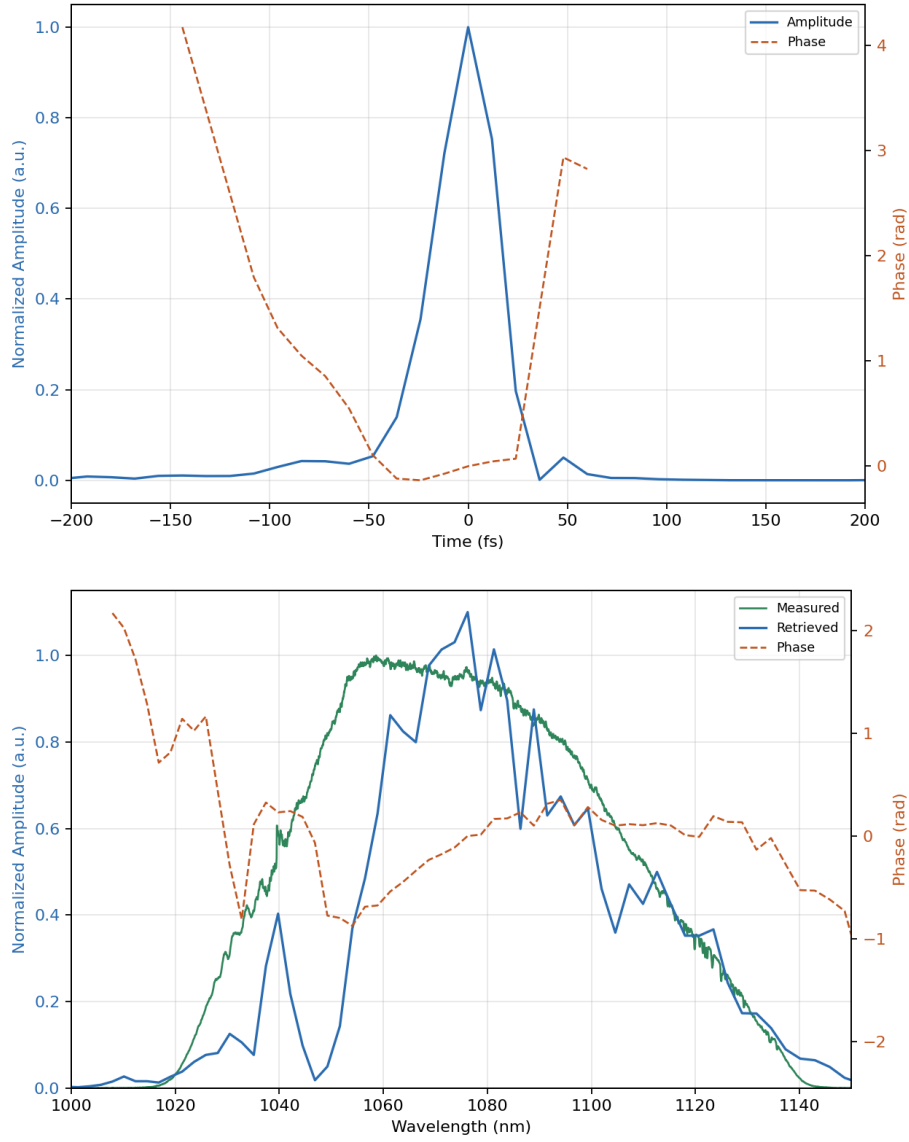


Figure 4.9: Retrieved temporal intensity and phase (top) and retrieved spectral amplitude and phase compared with the independently measured OSA spectrum (bottom) for the compressed pulse at 10 A.

Starting from the retrieved pulse of the FROG measurement, we computed the intensity autocorrelation function. In Figure 4.10 shown the comparison between the FROG-retrieved autocorrelation and the autocorrelation trace acquired by the autocorrelator. As it can be seen, the two measurements are in fairly good agreement.

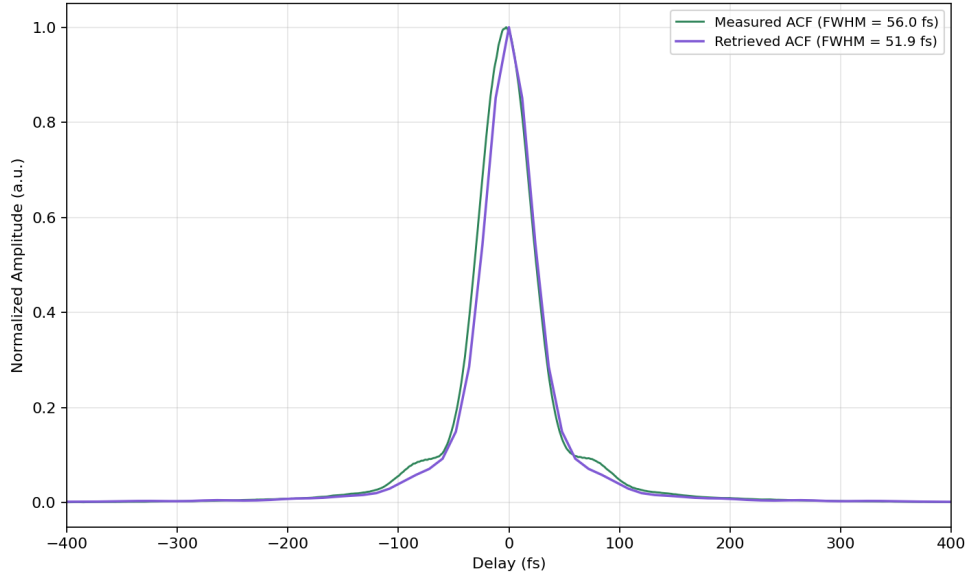


Figure 4.10: FROG-retrieved autocorrelation compared with the autocorrelation trace measured independently in standard (non-FROG) acquisition mode, both peak-normalized and peak-centered.

To assess how far the pulse duration we obtained is from the minimum pulse duration that can be sustained by the optical spectrum we measured, we decided to compute the inverse Fourier transform of the measured spectrum, assuming a constant spectral phase, thus determining the minimum possible pulse duration. Once we obtained the Fourier-limited pulse, we computed its autocorrelation function and compared its FWHM to the FWHM of the autocorrelation trace of the real pulse we measured in the lab. This gives an estimation of how close the actual pulse duration after compression is to the Fourier limit.

In Fig. 4.11 shown the intensity profile of the pulse obtained by computing the inverse Fourier transform of the spectrum (top) and its corresponding autocorrelation function (bottom), which has a FWHM of 33.1 fs and 44.7 fs, respectively. For comparison, the FWHM of the autocorrelation trace measured for the real pulse is ~ 56.7 fs. This suggests that the time-bandwidth product of the pulses we obtained is about only 26% larger than the Fourier limit.

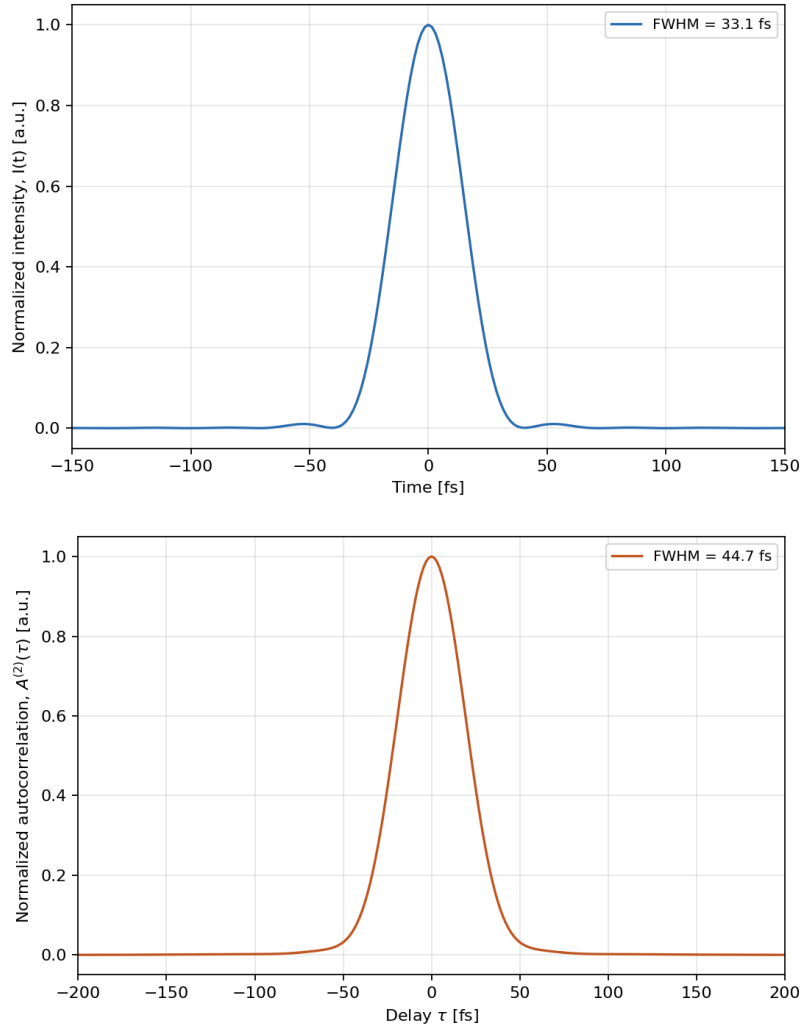


Figure 4.11: Reconstructed Fourier-transform-limited temporal intensity profile from the measured OSA spectrum at 10 Å under the flat-phase assumption (top) and its autocorrelation (bottom).

4.6 Influence of the seed spectrum

Following the characterization of the amplified and compressed pulses, an additional experimental investigation was carried out to assess the influence of the seed spectral bandwidth and pulse duration on the subsequent amplification and compression processes. The aim was to investigate how different initial spectral conditions affected the nonlinear evolution of the pulse in the active fiber and the characteristics of the compressed output.

At this stage of the experiment, the oscillator cavity was already operating in a

stable configuration. Therefore, the aim was not to modify its overall geometry but rather to vary the seed spectral bandwidth while preserving the established cavity alignment and operating conditions as much as possible. Different approaches were consequently explored, including modifications of the pump power, adjustments of the SESAM alignment and focusing conditions, changes in the intracavity dispersion, and external spectral filtering of the oscillator output. These approaches allowed seed pulses with different spectral bandwidths to be obtained without introducing major modifications to the established cavity configuration.

The following subsections describe the two investigated cases. First, a broader seed spectrum was generated by reducing the amount of negative intracavity dispersion and increasing the oscillator pump power to assess whether a wider seed bandwidth could improve the compressed pulse characteristics. The resulting trend observed with the broadband seed configurations then motivated a complementary investigation in the opposite direction, in which the seed bandwidth was instead reduced below the nominal oscillator value, to verify whether the same trend held and to establish where, within the accessible range of seed bandwidths, the amplifier performance was actually optimized. For each configuration, the most representative results were selected for comparison. The corresponding amplified spectra and compressed pulse characteristics were evaluated at the maximum amplification level investigated for each seed condition.

4.6.1 Broadband seed

A complementary approach was investigated to increase the spectral bandwidth of the seed pulse. In this case, the spectral evolution of the oscillator was modified by reducing the amount of negative intracavity dispersion. The GTI mirror providing approximately -1200 fs^2 of dispersion was removed and replaced with a GTI mirror providing approximately -550 fs^2 .

The reduction of the negative intracavity dispersion allowed the oscillator to operate with a broader spectral bandwidth. The pump power was then increased, while the alignment and focusing conditions were also adjusted to further increase the spectral width of the generated pulses. By combining these adjustments, seed

spectra with bandwidths of approximately 7 nm and 10 nm were obtained. The corresponding broader-band seed pulses were subsequently injected into the same GMNA amplification system. As for the narrow-band configuration, the amplified spectra were recorded at the maximum amplification level investigated for each seed condition, and the resulting compressed pulses were characterized by intensity autocorrelation. The comparison between the different broadband seed conditions provides an additional assessment of how the initial spectral bandwidth affects the nonlinear spectral broadening and the final pulse duration after compression.

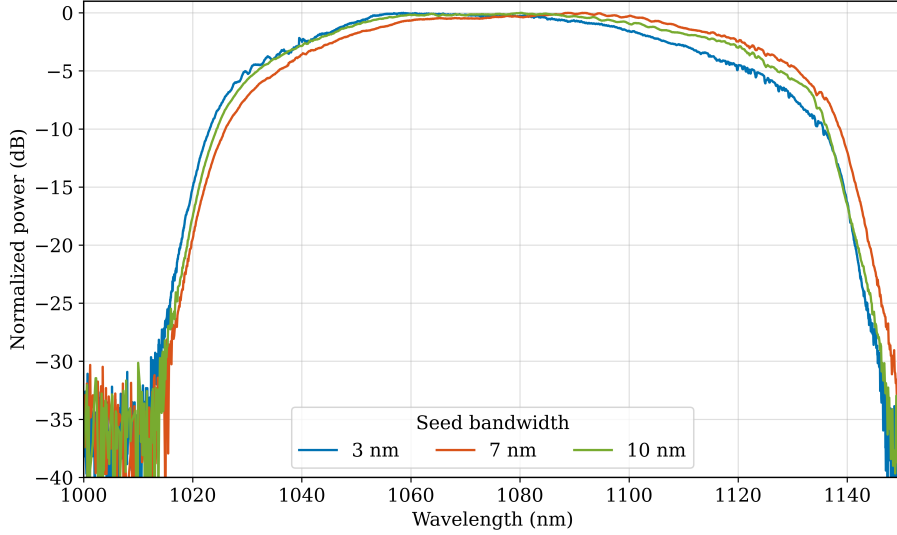


Figure 4.12: Normalized amplified spectra at maximum pump current (10 A) for the 3 nm, 7 nm and 10 nm seed configurations.

Figure 4.12 compares the normalized amplified spectra obtained at maximum pump current (10 A) for the 3 nm, 7 nm and 10 nm seed configurations. The spectral shape retains the characteristic flat-top ("loaf-shaped") profile typical of the GMNA regime in all three cases, with the -10 dB and -20 dB bandwidths remaining nearly unchanged (112 nm to 113 nm and 123 nm to 124 nm, respectively). The main difference appears near the top of the spectrum, where the -3 dB bandwidth increases from 72.6 nm (3 nm seed) to 79.4 nm (7 nm seed) and 81.5 nm (10 nm seed).

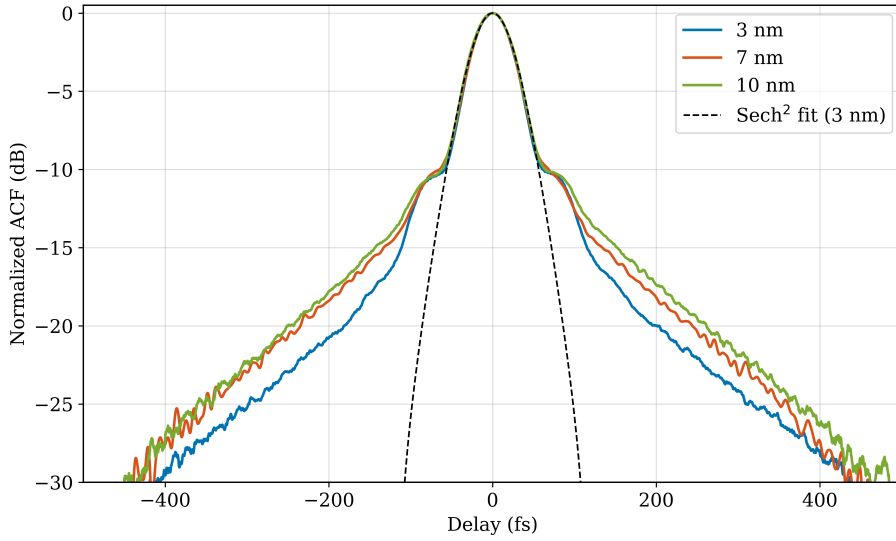


Figure 4.13: Normalized intensity autocorrelation traces (logarithmic scale) of the compressed pulses for the 3 nm, 7 nm and 10 nm seed configurations, together with a representative sech^2 fit.

The corresponding compressed pulses were characterized by intensity autocorrelation, shown in Figure 4.13 on a logarithmic scale to highlight the pedestal. All traces were fitted with a Sech^2 pulse shape, yielding deconvolved pulse durations of 37.4 fs ($R^2 = 0.989$), 38.1 fs ($R^2 = 0.987$), and 39.0 fs ($R^2 = 0.984$) for the 3, 7, and 10 nm seed bandwidths, respectively.

Despite the increase in -3 dB spectral bandwidth, the broader-band seed configurations did not yield shorter compressed pulses: the three cases remain within a comparable 37 fs to 39 fs range. A more significant difference appears in the pedestal of the autocorrelation trace, where the wings at the -10 to -20 dB level become progressively broader as the seed bandwidth increases, indicating a more pronounced and extended pedestal around the main pulse. This behavior is consistent with a growing fraction of the additional spectral energy not being ideally compressed by the grating compressor – likely due to uncompensated higher-order spectral phase – rather than translating into a genuine reduction of the compressed pulse duration.

4.6.2 Narrow-band seed

The first experimental approach consisted of reducing the spectral bandwidth of the seed pulse regarding the nominal oscillator output. Initial attempts were made by modifying the alignment and focusing conditions at the SESAM, as well as by varying the oscillator pump power. These adjustments allowed the seed spectrum to be modified to some extent but were not sufficient to obtain the desired reduction in bandwidth while maintaining stable oscillator operation: the intracavity dispersion and mode-locking conditions established in Chapter 3 did not allow the oscillator bandwidth to be reduced below its nominal value of approximately 3.2 nm while preserving stable, self-starting soliton mode-locking. To obtain a more controlled reduction of the spectral bandwidth, a Semrock spectral filter was therefore introduced at the output of the oscillator. The filter was used to directly limit the spectral content of the pulse injected into the amplification stage, providing a narrower-band seed while leaving the internal geometry of the oscillator unchanged. This approach was motivated by the results of the broadband seed investigation discussed in Section 4.6.1, which suggested that a narrower seed bandwidth could further improve the compressed pulse quality; the filter was therefore employed to test whether reducing the seed bandwidth below the oscillator's nominal value would provide any additional benefit. The main drawback of this approach was a reduction of approximately 50% in the seed power delivered to the amplifier, caused by the finite transmission of the filter combined with the polarization optics along the seed delivery path.

The filtered seed pulse had a duration of 657.5 fs and a pulse quality of 0.989, indicating a nearly transform-limited pulse; assuming a sech^2 profile close to the transform limit, this duration corresponds to an estimated spectral bandwidth of approximately 1.7 nm, narrower than the nominal 3.2 nm oscillator output.

The resulting narrow-band seed was subsequently injected into the same GMNA system described in the previous sections. The amplified spectrum, recorded at the maximum investigated pump current of 10 A, is shown in Fig. 4.14. The amplified spectrum extended over a -3 dB bandwidth of approximately 76 nm, centered around 1076 nm, closely matching the amplified bandwidth obtained under the

same pump current with the unfiltered, nominal-bandwidth seed (Table 4.1).

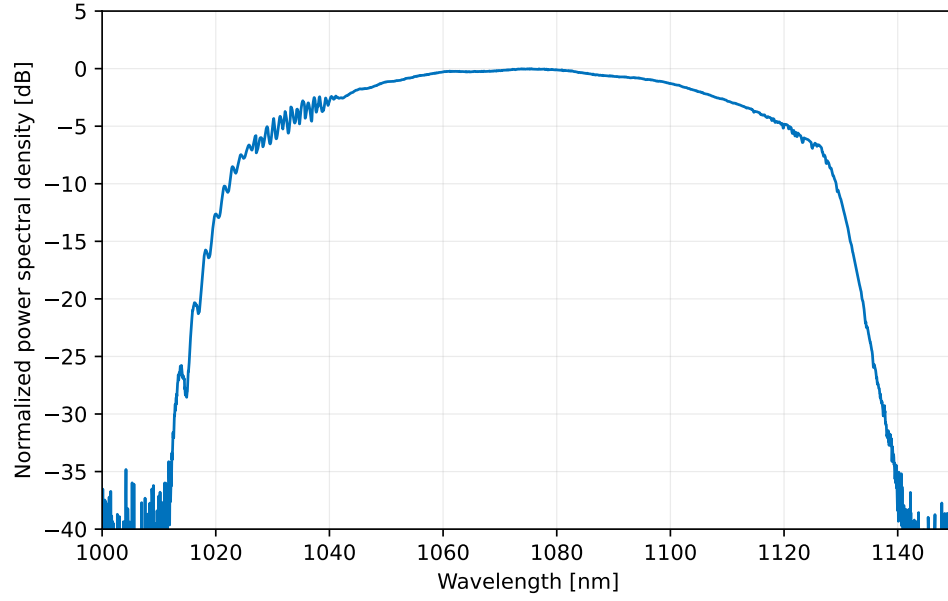


Figure 4.14: Amplified optical spectrum at a pump current of 10 A obtained with the spectrally filtered, narrow-band seed.

The corresponding compressed pulse was characterized by intensity autocorrelation, shown in Fig. 4.15 together with the sech^2 fit. The compressed pulse duration was 37.9 fs with a pulse quality of 0.89.

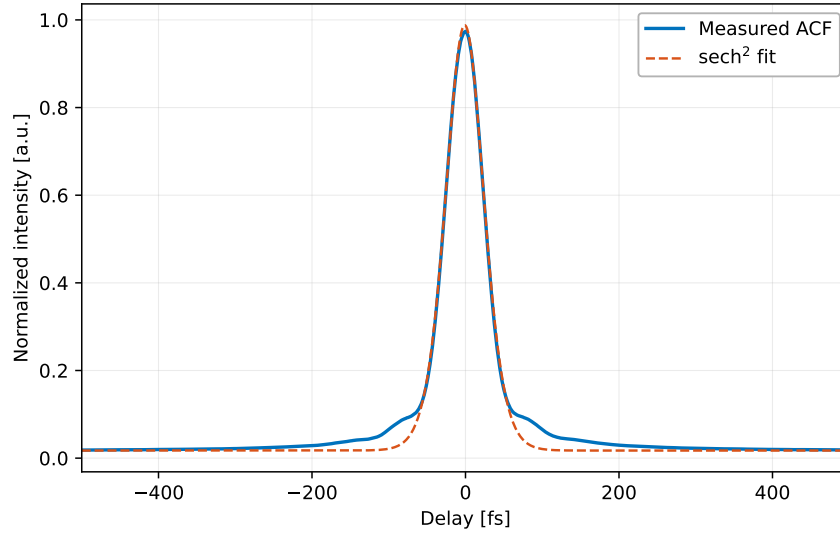


Figure 4.15: Intensity autocorrelation trace of the compressed pulse obtained from the narrow-band, spectrally filtered seed at 10 A pump current, together with the corresponding sech^2 fit.

Both the amplified spectrum and the compressed pulse duration and quality obtained with the filtered, narrow-band seed were remarkably similar to those obtained with the unfiltered, nominal-bandwidth (3.2 nm) seed under the same pump current (37 fs, pulse quality 0.90, Section 4.5.3). Given the substantial seed power penalty introduced by the filter, and the absence of any measurable improvement in the compressed pulse characteristics, the spectral filter was not retained in the final amplifier configuration. This result, however, provides useful experimental evidence that the nominal oscillator bandwidth of approximately 3 nm already represents close to the optimal seed condition achievable with the present seeder-amplifier configuration, consistent with the narrow-band, soliton-limited oscillator design discussed in Section 3.7.3.

4.6.3 Discussion

Table 4.2 summarizes the output power, compressed pulse duration, and pulse quality obtained for the three seed spectral bandwidths investigated at increasing amplifier pump current.

For all three seed conditions, the amplifier delivered comparable output power at a given pump current, and the compressed pulse duration converged toward similar values in the range of 37–39 fs, at the maximum investigated pump current. This indicates that, at sufficiently high pump power, the nonlinear evolution inside the active fiber becomes the dominant factor determining the compressed pulse duration, largely independent of the initial seed bandwidth. The pulse quality, however, shows a clear and systematic dependence on the seed condition that is not apparent from the compressed duration alone. At every pump current investigated, the narrow-band, soliton-limited seed developed in Chapter 3 yielded the highest pulse quality, decreasing from 0.95 at 4 A to 0.90 at 10 A. The broader-bandwidth seed conditions, by contrast, consistently produced lower pulse quality at every pump current, down to 0.83–0.85 at 7 A for the broadest seed investigated. This indicates that, while the amplifier can compress seed pulses of markedly different initial bandwidths to comparable durations, the fraction of energy contained in the main pulse, rather than in the uncompressed pedestal, is systematically higher

for the narrower, soliton-limited seed. This result confirms that the narrow-band oscillator design adopted in this work, described in Section 3.7.3, was an effective choice for the GMNA seed source, providing not only a well-defined and predictable amplification behavior but also the best achievable pulse quality after compression.

Seed BW / duration	Pump current	Output power	Compressed τ	Pulse quality
3.5 nm / 370 fs	4 A	1.35 W	52.4 fs	0.95
	7 A	2.92 W	43 fs	0.93
	10 A	4.34 W	37 fs	0.90
7.2 nm / 168 fs	4 A	1.52 W	70 fs	0.87
	7 A	3.03 W	47 fs	0.85
	10 A	4.44 W	37.7 fs	0.88
10.5 nm / 122 fs	4 A	1.54 W	75.5 fs	0.84
	7 A	3.12 W	48.6 fs	0.82
	10 A	4.50 W	38.8 fs	0.87

Table 4.2: Output power, compressed pulse duration (τ), and pulse quality for the three seed spectral bandwidths investigated at increasing amplifier pump current.

As discussed in Section 4.5.3, the FROG characterization confirmed that the compressed pulse duration can be reliably assessed by directly comparing the measured autocorrelation trace with the autocorrelation of the Fourier-transform-limited pulse reconstructed from the measured spectrum. The same approach was extended to all seed bandwidth and pump current conditions investigated; the resulting FWHM values, rounded to the nearest femtosecond, and the corresponding ratio between the measured and Fourier-limited time-bandwidth product ($\text{TBP}/\text{TBP}_{\text{FL}}$) are summarized in Table 4.3. This analysis clearly shows that seeding with the narrower bandwidth results in a compressed pulse duration much closer to the Fourier-transform limit at every pump current. This suggests that the GMN amplifying regime is reached sooner, permitting a close to optimal pulse compression with the grating pair compressor already at low pump power level, further confirming that this is the best seeding choice for our MOPA laser.

Seed BW	Pump current	Measured FWHM	Fourier-limited	TBP/TBP _{FL}
3.5 nm	4 A	77 fs	63 fs	1.22
	7 A	62 fs	51 fs	1.22
	10 A	57 fs	45 fs	1.27
7.2 nm	4 A	98 fs	63 fs	1.56
	7 A	68 fs	50 fs	1.36
	10 A	58 fs	44 fs	1.32
10.5 nm	4 A	98 fs	64 fs	1.53
	7 A	71 fs	50 fs	1.42
	10 A	60 fs	44 fs	1.36

Table 4.3: Measured autocorrelation FWHM, Fourier-transform-limited autocorrelation FWHM, and ratio between the measured and Fourier-limited time-bandwidth product (TBP/TBP_{FL}) for all investigated seed bandwidths and pump currents.

Conclusions

This thesis presented the design, realization, and experimental characterization of a hybrid master-oscillator power-amplifier system, combining a SESAM mode-locked Yb:KYW bulk laser oscillator with a GMN fiber amplifier stage.

As discussed in the Introduction, fully fiber-based oscillator-amplifier systems are attractive for their compactness and reduced alignment complexity, and the research group's prior work has extensively explored such all-fiber platforms. However, achieving a specific target repetition rate, dictated, for instance, by the requirements of a subsequent synchronously pumped optical parametric oscillator operating with a free-space cavity of several meters, is considerably more flexible with a bulk solid-state oscillator than with a fiber-based one, whose cavity length is constrained by the minimum length of doped fiber required for adequate gain and dispersion management. This consideration motivated the hybrid architecture developed in this work: a bulk oscillator providing direct, flexible control over the repetition rate, combined with a fiber-based GMNA amplifier stage to reach the pulse energies required for downstream applications.

The Yb:KYW oscillator, designed and characterized in Chapter 3, delivered stable, self-starting soliton mode-locked pulses at 60 MHz, with a duration of 367 fs and a time-bandwidth product close to the transform limit for a sech^2 pulse, confirming stable, nearly Fourier-limited operation directly from the oscillator. The theoretical stability criterion against Q-switched mode-locking, developed from first principles in Chapter 1 and applied to the specific cavity design in Section 3.4, was consistent with the robust, self-starting operation observed experimentally across all the output-coupler transmissions investigated.

The GMNA amplifier, whose implementation benefited from established expertise

within the research group with this amplification technique, delivered up to 4.4 W of average output power at a pump power of 9 W, with the seed pulse spectrally broadened by more than a factor of twenty and subsequently compressed to durations as short as ~ 37 fs. The compressed pulses were shown to lie within $< 10\%$ of the Fourier-transform limit associated with their actual, GMNA-broadened spectral shape, rather than that of an idealized pulse profile, indicating that the double-pass grating compressor recovered nearly all the usable bandwidth generated by the nonlinear amplification process.

The central experimental focus of this work was the investigation of how the seed spectral bandwidth affects the performance of the GMNA stage, presented in Section 4.6. While the compressed pulse duration converged to comparable values (37–39 fs) regardless of the seed bandwidth at sufficiently high pump current, the pulse quality showed a clear and systematic dependence on the seed condition: the narrow-band, Fourier-limited seed developed in this work consistently yielded the highest pulse quality (0.90–0.95), while broader seed bandwidths resulted in a measurably larger fraction of the pulse energy remaining in the uncompressed pedestal (0.83–0.88). This result provides direct experimental confirmation that the spectral characteristics of the seed oscillator are not merely a secondary design parameter, but a significant factor in determining the achievable compressed pulse quality – validating the narrow-band oscillator design strategy adopted in this work and demonstrating that a comparatively simple, few-milliwatt bulk seed source, combined with an established GMNA architecture, can deliver a high-quality, high-power ultrashort-pulse source with good power extraction efficiency.

Several directions remain open for future work. From the amplifier side, as discussed in Section 2.4, the pulse energy achievable from a standard single-mode active fiber is ultimately limited by the onset of stimulated Raman scattering; extending the amplifier to a large-mode-area active fiber, following the approach demonstrated by Sidorenko and Wise [19], represents a natural next step to further scale the output pulse energy, and the average power levels already achieved in this work with a standard fiber suggest that seeding such a large-mode-area amplifier should be readily achievable with the present bulk oscillator. From the

system side, the original motivation for developing a flexible, higher-repetition-rate bulk-seeded platform was to provide a suitable pump source for a synchronously pumped optical parametric oscillator with a free-space cavity; the source developed and characterized in this work represents a first step toward that goal, and its integration with such a system is a natural continuation of the present work.

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