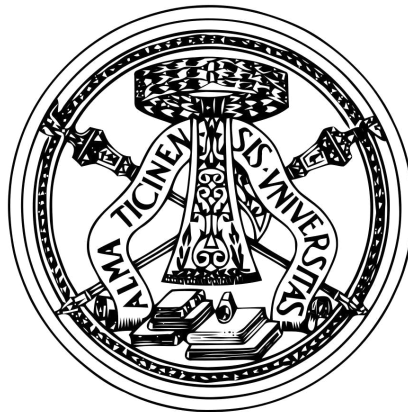




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PHD PROGRAM IN ELECTRONICS, COMPUTER SCIENCE AND ELECTRICAL
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Femtosecond amplifiers and oscillators pumped by high-brightness tapered-diode lasers

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Glossary

Acronymous

fs : Femtosecond

ps : Picosecond

CW : Continuous Wave

ML : Mode-Locking

SPM : Self-Phase Modulation

ASE : Amplified Spontaneous Emission

MOPA : Master Oscillator Power Amplifier

SESAM : Semiconductor Saturable Absorber Mirror

SAM : Saturable Absorber Mirror

GTI : Gires–Tournois Interferometer

GDD : Group Delay Dispersion

GVD : Group Velocity Dispersion

TBP : Time–Bandwidth Product

OC : Output Coupler

HR : High Reflectivity

AR : Anti Reflectivity

DM : Dichroic Mirror

PBS : Polarizing Beam Splitter

HWP : Half-Wave Plate

QWP : Quarter-Wave Plate

Q3L : Quasi-Three Levels

FI : Faraday Isolator

SHG : Second Harmonic Generation

BBO : Beta Barium Borate

OPCPA : Optical Parametric Chirped-Pulse Amplification

CEP : Carrier-Envelope Phase

QS : Q-Switched

KLM : Kerr-Lens Mode-Locking

DBR : Distributed Bragg Reflector

TA : Tapered Amplifier

LD : Laser diode

RW : Ridge Waveguide

MO : Master Oscillator

FWHM : Full Width at Half Maximum

NA : Numerical Aperture

FS : Fused Silica

BP : Brewster Plate

DHR : D-shaped High-Reflectivity Mirror

RFC : Regulable Fiber Collimator

AOM : Acousto-Optic Modulator

GR : Diffraction Grating

MFD : Mode Field Diameter

PWPS : Polarizing-Wave Plate Splitter

Yb:YAG : Ytterbium-doped Yttrium Aluminum Garnet

Yb:KYW : Ytterbium-doped Potassium Yttrium Tungstate

Yb:KGW : Ytterbium-doped Potassium Gadolinium Tungstate

Yb:YLF : Ytterbium-doped Yttrium Lithium Fluoride

Yb:CaF₂ : Ytterbium-doped Calcium Fluoride

Yb:CALGO : Ytterbium-doped Calcium Gadolinium Aluminate

Symbols

M^2 : Beam quality factor

M_p^2 : Beam quality factor of the pump beam

$\varnothing$: Fiber core diameter

θ_0 : Diffraction angle

w_p : Pump spot radius

A_p : Pump beam area

z_R : Rayleigh length

L_c : Crystal length

g_0 : Small-signal gain coefficient

λ : Wavelength

λ_L : Laser wavelength

λ_p : Pump wavelength

λ_s : Seeder wavelength

λ_c : Pulse central wavelength

$\Delta\lambda$: Spectral pulse width

$\Delta\lambda_i$: Seeder spectral pulse width

$\Delta\lambda_o$: Output spectral pulse width

$\Delta\lambda_g$: Active medium gain bandwidth

τ_0 : Transform-limited-pulse duration

τ : Chirped pulse duration

τ_i : Input seeder pulse duration

τ_o : Output pulse duration

P_{out} : Output power

P_{seed} : Seeder power

P_p : Incident pump power

P_{abs} : Absorbed pump power

P_{in} : Input seed power

P_{peak} : Peak power

P_L : Saturation power

P_{th} : Threshold absorbed pump power

P_{ASE} : ASE power

E_t : Thermal quantum energy

T : Temperature (Kelvin degree)

E_p : Pulse energy

E_G : Gain saturation energy

E_S : SESAM saturation energy

ΔR : SESAM modulation depth

G : Amplifier gain

G_0 : Small-signal gain

g : Gain coefficient

g_0 : Small-signal gain coefficient

g_{th} : Gain at threshold

σ_e : Emission cross-section

σ_a : Absorption cross-section

σ_{eff} : Effective cross-section

β : Population inversion factor

N : Number of passes / generic count

N_{tot} : Total ion population

N_1 : Ground-state population

N_2 : Excited-state population

n : Refractive index

n_e : Extraordinary refractive index

n_o : Ordinary refractive index

n_2 : Non-linear refractive index

w_s : Seed beam waist

w_0 : Beam waist

b : Confocal parameter

L : Propagation length

l : Grating distance

L_g : Gain length

L_{eff} : Effective path length

Ω : Solid angle

I : Intensity

I_{out} : Output intensity

I_L : Saturation intensity

I_{SP} : Saturation pump intensity

I_P : Pump intensity

η_{opt} : Optical-to-optical efficiency

η_0 : Asymptotic efficiency

η_{slope} : Slope efficiency

R_{OC} : Output coupler reflectivity

T_{OC} : Output coupler transmission

ℓ_c : Round-trip cavity losses

ℓ_a : Reabsorption losses

θ_B : Brewster angle

θ_i : Incidence angle

θ_t : Transmitted angle

$\theta_{Littrow}$: Littrow angle

ρ : Walk-off angle

δx : Lateral walk-off displacement

R_s : Reflectivity at the interface

m : Diffraction order

d : Grating period

B : Nonlinear phase (B-integral)

τ_f : Fluorescence lifetime

h : Planck constant

c : Speed of light

k_b : Boltzmann constant

Δx : Lateral chromatic displacement

f : Focal length

$\Delta\nu_{eff}$: Effective bandwidth

w_g : Waist in the active medium

$dx/d\lambda$: Spatial dispersion

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Abstract

This PhD thesis presents the development, optimization, and experimental characterization of compact femtosecond amplifiers and oscillators based on Ytterbium-doped materials, pumped by high-brightness tapered-diode laser modules. The work was carried out within a collaboration between the Laser Source Laboratory at the University of Pavia and Pantec Biosolutions AG (Liechtenstein). The aim of the work was to prove the potential of medium power (~ 10 W) high brightness ($M^2 < 2$) tapered diodes as pump source for high-gain, compact amplifiers based on readily available Yb-doped materials. During the final stages of my PhD, I also had the opportunity to test the same pump source in direct pumping of femtosecond oscillators, with the aim to demonstrate both high optical-to-optical conversion efficiency and short pulse duration (possibly < 100 fs).

The first part of the thesis concerns the detailed characterization of the tapered diode pump modules. Each module integrates two polarization-coupled diodes emitting at 978 nm and delivering up to 11 W optical power with a beam quality factor of $M^2 < 1.5$. The emission wavelength was highly stable, with a drift below 0.1 nm/A, and the beam remained close to diffraction-limited up to 9 A of driving current, corresponding to ~ 10 W output power. These results confirmed the suitability of the modules as pump sources for quasi-three-level Yb-doped materials.

A large variety of Yb-doped crystals capable of sub-100 fs pulse generation have been presented in literature in the last decade. However, among them, only a few have become available off-the-shelf. Research on laser materials is an ongoing process, but for my work I preferred to focus on those Yb-doped crystals that could be immediately employed in a commercial laser module and are available on the market offered by several different suppliers. For this reason, my choice fell on Yb:KYW, which is for sure one of the

most employed Yb-doped materials in industrial femtosecond lasers. Indeed, this laser material possesses several properties that makes it suitable for an high-gain amplifier still capable of ultrashort pulses amplification, namely:

- It possesses a high absorption cross section, well matched to the emission wavelength of the available tapered diodes, and sustains high doping level without severe worsening of its quite good thermo-optical properties. This permits the use of short and highly-doped crystals that sustain tight focusing of the pump required for high gain;
- The crystal is biaxial, hence birefringent, and the peak emission cross section is quite high, but broad enough to sustain sub-100 fs pulses and to effectively amplify pulses below 300 fs duration with reasonable gain narrowing.

The amplification experiments were based on single and double-pass geometries, and also on 4-passes geometry employing two Yb:KYW crystals oriented with the N_m crystallographic axes mutually orthogonal, in order to optimize the pump absorption in each crystal. We tried to exploit the key feature of the tapered diode pump, i.e. its high beam quality, by tightly focusing the pump in order to maximize the small signal gain. The excellent pump beam quality permitted to maximize also the spatial overlap between the pump and the TEM_{00} seed beam along the whole crystal length, at least for the configurations using a single Yb:KYW crystal. This is the reason why in this case we both obtained very high small signal gain (up to $G_0 \sim 40$ for ~ 10 mW seeder power in double pass) and high extraction efficiency when seeding with ~ 500 mW, thus operating closer to the saturation power of the amplifier (up to $> 50\%$ optical-to-optical extraction efficiency).

In the crossed-crystals setup, composed of two 3-mm Yb:KYW crystals with orthogonal N_m/N_p orientations and pumped by the dual-diode module, we achieved a gain $G \approx 100$, in the low-injection seeder power regime and 30% optical-to-optical efficiency, corresponding to a maximum output power of about 3 W. Spatial beam quality was excellent in all tested setups, with $M^2 < 1.1$ even at the maximum absorbed pump power in

every configuration, which is a further confirmation of the very good pump beam quality and mode matching realized in the amplifiers.

During a visiting period of 6 months at Pantec Biosolutions, I had the opportunity to build a four-pass crossed crystal amplifier similar to the one previously developed at the University of Pavia, and to test it in a Master Oscillator Power Amplifier (MOPA) setup made of a fiber laser seeder providing chirped ps pulses with an optical spectrum of ~ 15 nm, centered at about 1035 nm, and followed by an Acousto-Optic pulse picker to down-scale the pulse repetition rate before amplification, in order to increase the energy per pulse after the amplifier. This is the front-end of a typical industrial fs MOPA system, in which the stage I designed is supposed to play the crucial role of the high-gain pre-amplifier, responsible of restoring the pulse train average power from few tens of mW after pulse picking to few W. The study carried out in Pavia and the optimized design I realized permitted to build a compact and very efficient amplifier. Thanks also to a slightly higher available pump power, we could even improve the performance with respect to previous experiments and we demonstrated a four-passes small signal gain $G_0 \sim 500$ and very good amplifier efficiency, despite the low seeder average power. At 15 mW seeder power we obtained up to 1.5 W output power with ~ 200 fs pulse duration after compression. At 40 MHz pulse repetition rate, this corresponds to > 37 nJ pulse energy and ~ 190 kW pulse peak power.

In the final part of my research activity, the tapered-diode pump module was employed to directly pump femtosecond oscillators. Two configurations were investigated: a Yb:CaF₂ laser and a Yb:YLF laser. The Yb:CaF₂ system achieved stable continuous-wave operation and reliable mode-locking using a SESAM and prism-based dispersion compensation, delivering 170 fs pulses at 1040 nm with up to 3 W output power, 20 nJ pulse energy and approx 120 kW peak power at 9 W incident pump power.

The Yb:YLF oscillator achieved 93 fs almost transform-limited pulses at 1040 nm, 2.2 W average power, 16 nJ pulse energy, and 170 kW peak power, representing one of the most interesting results (compared in literature) obtained to date for diode-pumped Yb:YLF oscillators. The experimental results demonstrate that tapered-diode pumping

can enable high optical-to-optical efficiency, excellent beam quality, and state of the art performance in terms of pulse duration. Further investigations about an optimized Yb:YLF femtosecond laser are ongoing.

Introduction

Over the past two decades, ultrafast laser systems operating in the picosecond (ps) and femtosecond (fs) regimes have transitioned from being almost exclusively laboratory devices to become indispensable tools in various industrial and scientific applications. This shift has been propelled by significant advancements in laser materials research, pump diode technologies, and fiber laser architectures.

In the realm of bulk solid-state lasers, ultrafast sources emitting around 1 μm wavelength, typically configured in a Master Oscillator Power Amplifier (MOPA) architecture, remain unparalleled for applications demanding high peak power and very good spatial and spectral purity[1],[2]. Specifically:

- Picosecond Regime: Laser systems utilizing neodymium-doped materials, such as Nd:YVO and Nd:YAG, continue to represent the state of the art, offering robust performance and mature technology.
- Femtosecond Regime: diode-pumped Ytterbium-doped crystals, including Yb:YAG, Yb:KYW, and Yb:CALGO, have become prevalent because of their favorable emission bandwidths, high quantum efficiency, good thermo-optical and thermo-mechanical properties. Yb-doped materials are so efficient and reliable that they basically substitute Ti:Sapphire lasers for all applications in which a pulse duration of the order of 100 fs is short enough [3].

Amplifying femtosecond pulses in bulk media presents unique challenges, primarily due to the relatively low gain per pass typical of materials with very broad emission cross section. Consequently, many commercial systems employ regenerative amplifiers (see Fig. 1), which simultaneously permit to have very high gain and high energy/power

extraction efficiency. Indeed regenerative amplifiers consist of a laser cavity where a low energy seed pulse is injected and remains trapped until full saturation of the gain occurs. This approach offers several advantages: it allows flexible control of the repetition rate through pulse picking, provides extremely high gain (on the order of 10^6 – 10^7), and operates in a saturated regime, making it a highly efficient optical system. However, regenerative amplifiers also present drawbacks similar to those of laser cavities, including alignment sensitivity. In addition, they are inherently complex, bulky, and expensive, mainly due to the fast electro-optical switch that is required to trap and extract the laser pulse from the cavity which ultimately limits their scalability and integration into compact and cost-competitive setups.

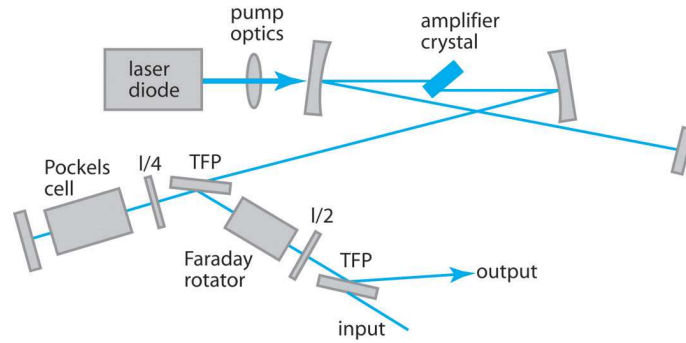


FIGURE 1: Regenerative amplifier configuration [4].

An alternative approach involves multi-pass amplification, where the seed pulse traverses the gain medium multiple times. Depending on the number of passes and the optical layout, multi-pass systems can range from relatively simple to optically intricate. However, even in the most complex configurations, they tend to be more compact and cost-effective than regenerative systems, since they do not require any electro-optical switch to couple-in and extract the pulse from the resonant cavity.

The advantage of multi-pass amplifier systems progressively diminishes as the number of passes increases. In order to operate efficiently, the gain-per-pass in the amplifier must be sufficiently high so that saturation is achieved within a limited number of traversals of the active medium, typically no more than 2–4 passes. If, on the contrary, the gain-per-pass is too low, a much larger number of passes is required, making the system

bulky, more sensitive to misalignment, and overall less attractive in terms of efficiency and robustness.

The small-signal gain, G_0 , is essentially determined by two main factors: the intrinsic properties of the active medium, namely its cross-section, and the pump intensity.

A higher emission cross-section directly increases the achievable gain for a given inversion density, whereas a higher pump intensity enhances the population inversion and thus leads to a larger G_0 .

At this point, the brightness of the pump source becomes a critical parameter. Indeed, the maximum power that can be deposited in a certain volume of a solid-state gain medium is limited by thermal effects: excessive heat density leads to strong thermal gradients, stress-induced birefringence, and, ultimately, crystal fracture. To mitigate these effects, longer crystals with lower doping concentration are employed, thereby distributing the absorbed pump power over a larger volume. However, if the pump brightness is not sufficiently high, the pump spot size cannot be reduced indefinitely, which imposes a lower limit on the pump beam area. This limitation ultimately constrains the achievable pump intensity and thus the small-signal gain.

Conversely, a high-brightness pump beam can be tightly focused into a nearly diffraction-limited spot, maximizing the inversion density and consequently the gain within the active medium. This allows the amplifier to reach the saturation within few passes, even when seeded with relatively low-power signals.

A significant limitation in this context arises from the available power of high-brightness, diffraction-limited pump sources. Single-emitter diodes typically provide a maximum power of ~ 1 W in an $M^2 \sim 1$ beam quality at 940-980 nm, which is the pumping window of Yb-doped laser materials. For a multi-mode broad-area single emitter, this value can grow to ~ 10 W. Actually, several single emitters can be coupled into the same multi-mode fiber, up-scaling the total power. E.g., commercially available modules at 976 nm can provide up to ~ 150 W in a $\varnothing = 105\ \mu\text{m}$ diameter fiber with $NA = 0.22$. The corresponding M^2 factor of the pump beam out of the fiber can be estimated from the diameter

of the fiber and the numerical aperture

$$M^2 \sim \frac{NA}{\theta_0} \sim \frac{NA}{2\lambda/(\pi\phi)} \sim 35$$

In the design of an amplifier, (but this is true also for oscillators) the pump beam area A_p must be large enough to keep the pump "collimated" within the active medium length. Roughly, this means that the pump beam Rayleigh length z_R must be comparable to the crystal length L_c :

$$L_c \sim z_{R,pump} \propto \frac{A_p}{M_p^2}$$

where $A_p = \pi w_p^2$ is the area of the pump spot, and M_p^2 is the beam quality factor of the pump beam. Simultaneously, the combination of crystal length L_c and the doping concentration will be determined in order to guarantee efficient pump absorption. This means that, once the optimal crystal length has been chosen for a certain doping concentration, the product $M_p^2 \cdot L_c$ fixes the smallest possible pump beam area that can be used, hence the maximum small signal gain coefficient, since it is inversely proportional to the pump area:

$$g_0 \propto \frac{1}{A_p}$$

This means that, if the crystal length is fixed and the incident pump power is fixed, the gain per Watt that can be stored in the active medium is inversely proportional to M_p^2 . This clearly shows the benefit of a high brightness pump source.

Among the various high-brightness pump technologies investigated in the last decades, one of the most promising is the monolithic Master Oscillator Power Amplifier (MOPA) configuration implemented in tapered laser diodes [5]. The characteristics of these innovative devices are discussed more in details in Chapter 1.

The research activity described in this PhD thesis, is the result of a collaboration between the Laser Source Laboratory at the University of Pavia and Pantec Biosolutions, a company based in Ruggell, Liechtenstein, specialized in the development and integration of laser and optical systems for medical and industrial applications. Within this

collaboration, Pantec research and development division has engineered a new generation of prototype diode pump modules based on tapered amplifier technology, capable of delivering up to 11 W of optical power at 979 nm in a nearly diffraction-limited beam ($M^2 < 2$).

As a part of this collaboration, the newly developed pump module was experimentally tested at the University of Pavia, to assess its potential in enhancing the performance of compact multi-pass amplifiers for femtosecond pulses amplification. Among the large variety of Yb-doped active media suitable for generation and amplification of fs pulse presented in Literature lately, we decided to employ only materials widely available off the shelf and already established in industrial lasers, in order to develop an amplifier immediately ready to be engineered and possibly made commercially available. For this reason, for what concerns amplification experiments, I only used Yb:KYW, which is a workhorse in industrial fs systems operating at 1 μm .

During the research activity described in this dissertation, I had the opportunity to test several different configurations for the amplifier employing either a single tapered diode with a single active medium, or a power up-scaled tapered diode module using two-polarization coupled tapered diodes. This latter device was tested both in a single amplifying crystal scheme, and in a double amplifying crystal scheme exploiting two Yb:KYW samples properly oriented with their crystallographic axes in a way to optimize both gain and pump absorption in a two and four passes amplification scheme.

Additionally, at the end of my PhD, I had the possibility to test this innovative pump module for direct pumping of femtosecond oscillators. Although this activity could not be concluded during my PhD, the results I obtained in particular with Yb:YLF as active medium are very promising and this research is actually carried out by my colleagues at the Laser Source Lab of the University of Pavia.

The integration of high-brightness tapered laser diodes as pump sources in multi-pass

femtosecond amplifiers and mode locked oscillators represents a significant advancement in ultrafast laser technology. This approach offers a compact, efficient, and cost-effective alternative to traditional regenerative amplifier systems, with potential applications across various scientific and industrial fields. Moreover, tapered diodes sources for ML oscillator allow to get a pulse peak power out of the oscillator already sufficient for some applications without the need for a subsequent amplifier. Future work will focus on further optimizing the oscillator/amplifier design, exploring different gain media, and scaling the system for higher pulse energies and repetition rates.

This thesis is organized as follows:

- Chapter 1 is devoted to explaining the tapered diodes pump module structure, working principle and characterization.
- Chapter 2 is focused on the different spectroscopic characteristics of the laser materials I employed for the femtosecond amplifiers and oscillators.
- Chapter 3 treats the amplification experiments with the description of the various amplifier configuration we tested using Yb:KYW crystals as active medium.
- Chapter 4 shows the implementation of the high-brightness source to pump a femtosecond Yb:CaF₂ and Yb:YLF oscillator
- In the Conclusions I summarize the main results of this work and trace the future foreseeable steps of this research activity.

Chapter 1

Tapered Diodes

1.1 Tapered diode structure

Tapered diode devices integrate two electrically independent sections within a single monolithic structure: a ridge waveguide (RW) acting as the master oscillator (MO), which produces a high spatial beam quality, low-power, narrow-linewidth seed beam, and a tapered amplifier (TA) section that boosts the optical power while preserving beam quality. A schematic representation of a typical tapered laser diode is shown in Figure 1.1, highlighting characteristic geometries. Laser oscillation is initiated by injecting current into the RW, whose emission wavelength is finely controlled via a Distributed Bragg Reflector (DBR). Thermal tuning of the DBR, enabled by an integrated heater, allows precise adjustment of the grating's temperature, and thus, of the emission wavelength via thermal expansion.

The tapered amplifier section is specifically engineered to expand the mode area gradually along the propagation axis. This geometry enables high-power operation by supporting higher injection currents while mitigating nonlinear and thermal effects. Simultaneously, it preserves the close to diffraction-limited beam quality inherited from the master oscillator [5]. The broad output aperture of the tapered section, often several hundred microns wide, not only permits sustaining higher power, but also reduces the natural divergence of the output beam. The monolithic integration of the MO and TA sections results in a compact, mechanically robust device that eliminates the need for precise optical alignment, a significant advantage over externally coupled diode-laser

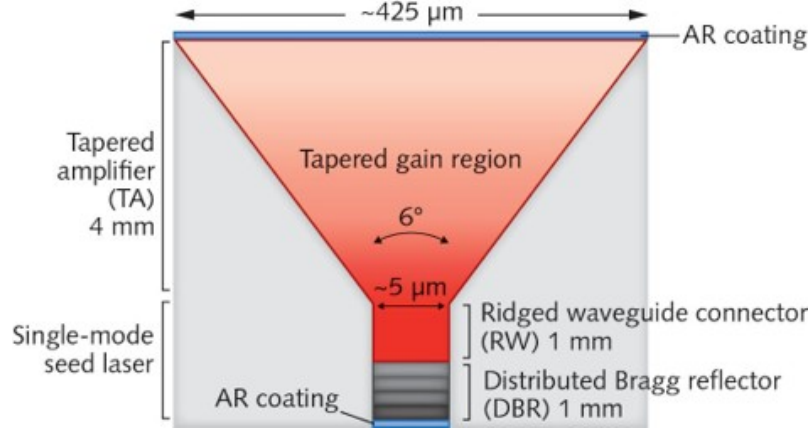


FIGURE 1.1: Tapered diode structure [6]

systems. However, this architectural choice imposes stringent requirements on fabrication processes and thermal management.

Historically, the widespread adoption of tapered diode lasers has been hindered by concerns regarding device lifetime and operational reliability. These challenges are primarily rooted in the thermal constraints associated with high-power operation. Additionally, the high small-signal gain intrinsic to the semiconductor amplifier makes these devices particularly susceptible to optical feedback. Reflections from downstream optical components or from directly illuminated targets can induce instabilities or even lead to irreversible damage, underscoring the need for careful system design and/or optical isolation of the tapered diode.

1.2 Pump module characterization

1.2.1 Laser module and electronic driver

Figure 1.2 illustrates the module housing the two tapered laser diodes. Although the module is equipped with sixteen electrical pins, only ten are used for the operation of both diodes. Specifically, three distinct electrical currents are supplied to the tapered amplifier (TA), the RW, and the DBR heater sections. As per standard convention, the symbols (+) and (–) denote the positive and negative terminals, respectively.

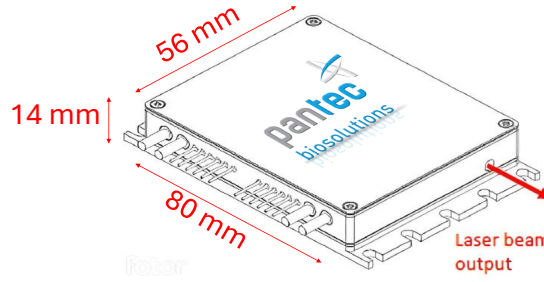


FIGURE 1.2: MiFem tapered diodes pump module and its dimensions

The operation of the MiFem module requires a dedicated driver, which is shown in Figure 1.3. To ensure effective thermal management, the module's heat sink must be cooled. In our experiments, we used water cooling with a chiller. An interlock mechanism is implemented in the system: if the chiller is turned off, the interlock will automatically shut down the pump unit, causing the system to enter a fault condition. Communication with the driver is established via a USB connection, linking the driver board to a control computer running the PuTTY software interface, which is a freely available SSH and telnet client.

The driver board includes two pairs of high-current connectors, one pair for each diode, labeled TA1 and TA2. These are designated for powering the tapered amplifier sections. In contrast, the lower-current lines for the RW and DBR heater elements are routed through a single 8-pin connector, which handles all the remaining control and supply signals.

1.2.2 Output power characterization

For all the measurements presented in this Section, the operational conditions were carefully set following the manufacturer's guidelines provided in the MiFem module operation manual. The RW and DBR currents were maintained at their recommended default values, i.e., 400 mA for the RW and 40 mA for the DBR heater, ensuring reliable laser emission with minimal wavelength drift. Furthermore, to guarantee thermal stability and prevent overheating of the diodes, the module was mounted on a water-cooled heatsink, and the cooling temperature was fixed at 15°C, as specified in the manual.

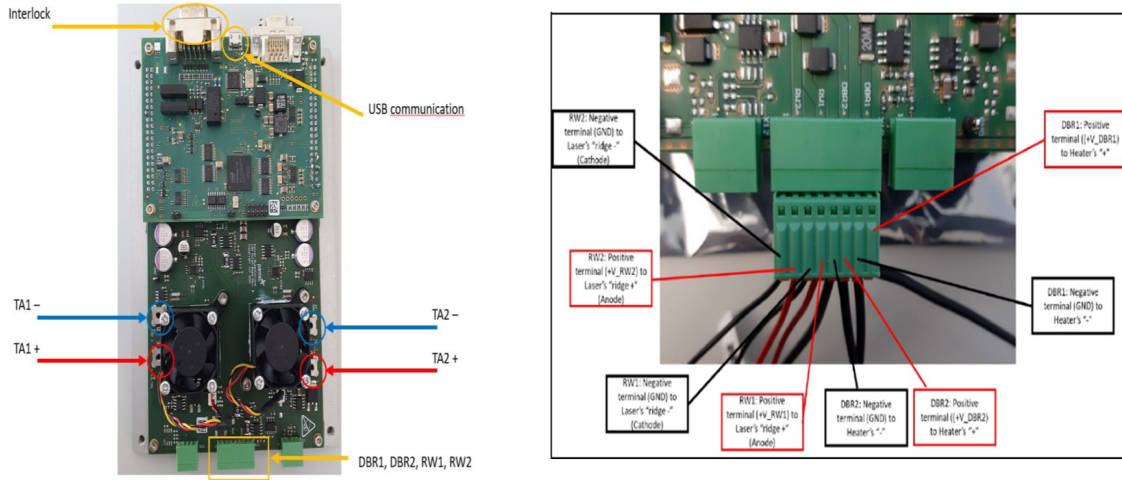


FIGURE 1.3: MiFem electronic driver board: On the right, 8-pin connector to control RW and DBR currents in detail

The results of the output power characterization as a function of the TA driving current are shown in Figure 1.4(a), where our experimental measurements are reported, and in Figure 1.4(b), which displays the reference characterization curves provided by Pantec Biosolutions in the official test documentation of the module. The comparison reveals that the only systematic difference between the two datasets arises from the presence of the Faraday isolator (85% transmission) placed in front of the pump diode in our setup to prevent back-reflections and potential damages. Once the optical isolator transmission is taken into account, the measured data exhibit an excellent agreement with the reference curves.

As shown in Figure 1.4, the output power increases with the TA current, following an almost linear trend, as expected. The two polarization-coupled tapered diodes have very similar performance, with LD2 slightly outperforming LD1 in terms of electrical-to-optical efficiency. The slope efficiency, defined as the rate of increase in output power per unit of current, was approximately 0.8 W/A for LD1 and LD2.

1.2.3 Wavelength stability characterization

One of the well-known characteristics and challenges of laser diodes is the dependence of their emission wavelength on both the device temperature and the driving current. In

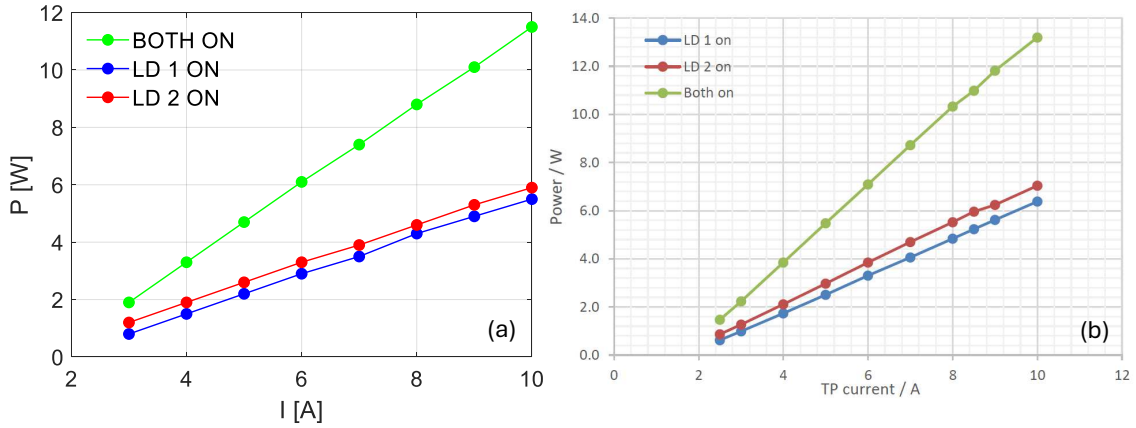


FIGURE 1.4: Output power curves as a function of the Tapered Diodes currents. (a) Data measured in the lab with the Farady Isolator in front of the module; (b) data provided by Pantec.

standard diode lasers, these dependencies can lead to significant wavelength drift during operation, especially under high-power or dynamically varying drive conditions, thus requiring proper active thermal control of the diode unit to guarantee a proper stability of the emitted wavelength. Such spectral instability poses a problem in many applications, particularly in cases where precise wavelength control or narrowband operation is essential, such as in high-resolution spectroscopy, pump-probe experiments, or nonlinear optics, but it is usually an undesired characteristic also in less demanding applications, such as diode pumping.

The MiFem laser module, however, addresses part of this problem through its Master Oscillator Power Amplifier (MOPA) configuration. In this architecture, the RW, acting as the MO, is operated at a fixed and stable current, thereby minimizing the current-induced drift of the emission wavelength at the source. The TA section, which boosts the optical power of the signal, is the only region where the injection current is varied. This separation between wavelength generation and power amplification provides a substantial advantage in terms of spectral stability and decouples the power tuning from wavelength control.

Furthermore, the thermally-controlled DBR allows for fine adjustments of the lasing

wavelength during operation. This feature helps to lock the emission at a target wavelength with high accuracy.

Nonetheless, while the MOPA design effectively mitigates current-induced shifts of the MO, it does not completely eliminate thermal effects arising from increased power dissipation in the TA section. As the TA current increases, heating due to Joule effect in the semiconductor becomes more pronounced, leading to a rise in the local temperature of the diode chip. Given the inherent temperature dependence of the semiconductor band-gap and refractive index, a small redshift in the emitted wavelength can still be anticipated, even though the seed wavelength from the MO remains fixed.

To quantify this effect and evaluate the practical stability of the emission wavelength under real operating conditions, we performed a dedicated series of spectral measurements. The emission wavelength was recorded at various TA currents while keeping the RW and DBR currents fixed at their nominal values (400 mA and 40 mA, respectively), as recommended by the manufacturer. The module was mounted on a water-cooled heatsink, and the chiller temperature was held constant at 15°C to ensure consistent thermal management during the tests. The measurements were first performed on diode LD1, followed by an identical set on diode LD2, to allow for comparison.

The results are presented in Table 1.1, where the emission wavelength is plotted as a function of the TA injection current. The data reveal a very modest wavelength drift, with a maximum observed shift of approximately 70 pm/A. This variation is practically negligible for most experimental setups and industrial applications. The measured spectral bandwidth remained extremely narrow at all current levels, indicative of the strong spectral filtering effect of the DBR. However, the spectral resolution of the optical spectrum analyzer (Ocean Optics HR-2000), used for the measurement was limited to 0.2 nm, which sets the detection threshold and may conceal even finer variations.

The MiFem module demonstrates excellent spectral stability under varying power conditions, a feature largely attributable to its MOPA configuration and the integrated DBR. This behaviour ensures reliable wavelength performance even when operating at

high output powers, making these tapered laser diodes particularly suitable for demanding applications where both high brightness and relatively narrow spectral linewidth are required.

I [A]	LD1 [nm]	LD2 [nm]
3	978.15	978.15
4	978.2	978.2
5	978.25	978.25
6	978.3	978.3
7	978.3	978.35
8	978.35	978.4
9	978.5	978.5
10	978.6	978.6

TABLE 1.1: Wavelengths output power for LD1 & LD2 as a function of the TA currents.

1.2.4 Beam quality and spatial profile characterization

The experimental setup used to characterize the spatial beam quality is depicted in Figure 1.5. The laser beam emitted by the diode sources was focused using a spherical lens with a focal length of $f = 40$ mm. A CCD camera with a resolution of 1288×964 pixels and a pixel size of $3.75 \mu\text{m}$ was employed to capture the beam intensity profile. To prevent the very sensitive sensor from saturating or being damaged, additional optical components—not shown in Fig. 1.5 were introduced. First, a half-wave plate together with a polarizing beam splitter was used to strongly attenuate the power for each diode separately. Further partial reflective elements were then added to reach the required power level of $\sim 100 \mu\text{W}$. We did not use any neutral density filter, since the local heating of the filter due to absorption lead to thermal aberrations in the transmitted beam, thus affecting the proper beam quality assessment. To map the evolution of the beam waist along the propagation axis (z), the CCD was translated along the focal region of the lens.

The beam waist measurements obtained from the CCD images (see Figure 1.6) were processed using a custom MATLAB script developed in the laboratory. The script analyzes the beam profiles and extracts the waist radius at each longitudinal position (z)

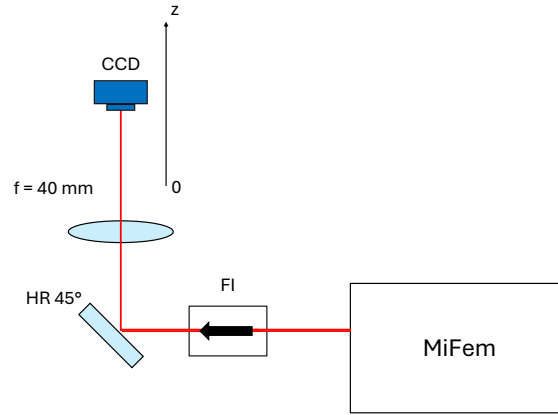


FIGURE 1.5: Z-scan beam quality measurements setup

using the 4-sigma method, a standard approach in spatial beam profile characterization [7]. By fitting the measured beam waist evolution at different TA currents, we could identify the following characteristics:

- For both laser diodes, when operated at currents above 9 A, the beam quality factor degrades substantially.
- Both diodes have shown a beam quality factor $M^2 < 1.6$ (slightly worse for LD1) up to the TA driving current of 9 A.
- At 9 A there is some residual ellipticity for LD2, whereas LD1 shows an almost perfectly circular beam.

Table 1.2 summarizes the beam quality measurements performed at different driving currents in the range of 5–9 A.

According to the beam quality results, the collimated $1/e^2$ waist at the output of the pump module was $w \sim \frac{\lambda f}{\pi w_f} \sim 500 \mu\text{m}$.

Given the dependence of the beam quality and beam waist dimension on the injection current, it is advisable to operate the diode module at a fixed current, such as 9 A, where a good trade-off between output power and spatial beam quality is achieved.

LD1 [A]	$z_{fx} - z_{fy}$ [mm]	w_x [μm]	w_y [μm]	M_x^2	M_y^2
5	1.1	21	23	1.3	1.3
6	1.5	25	22	1.4	1.6
7	0.9	24	23	1.5	1.6
8	1.2	23	18	1.5	1.4
9	0.5	20	18	1.6	1.2
LD2 [A]	$z_{fx} - z_{fy}$ [mm]	w_x [μm]	w_y [μm]	M_x^2	M_y^2
5	1.1	20	21	1.3	1.3
6	1.2	21	22	1.2	1.5
7	-0.7	24	23	1.5	1.5
8	-0.2	23	19	1.3	1.4
9	-0.3	25	18	1.2	1.2

TABLE 1.2: Beam quality characteristics for LD1 and LD2 operated at different currents.

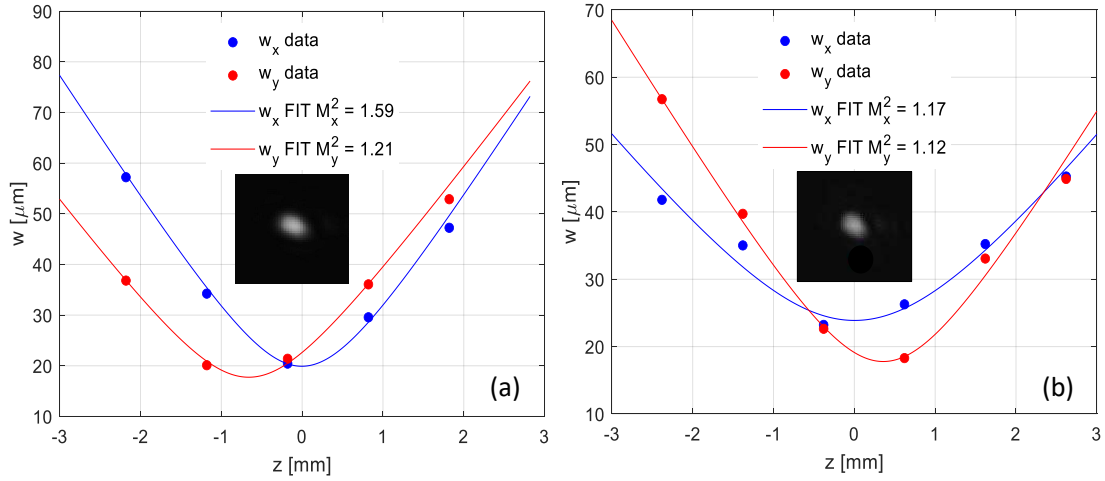


FIGURE 1.6: (a) LD1 and (b) LD2 spatial beam quality measurement results obtained at the TA current of 9 A. In the insets are shown the recorded beam profiles around the focal plane

Chapter 2

Quasi-3 levels materials

Quasi-three-level laser materials operating at $1\ \mu\text{m}$ are a crucial class of laser media for the generation and amplification of femtosecond pulses. These materials are doped with trivalent Ytterbium ions (Yb^{3+}) and exhibit a unique balance between energy-level scheme simplicity and lasing efficiency. Unlike classical four-level systems where the lower laser level is empty at room temperature, quasi-three-level systems suffer from re-absorption losses due to the thermal population of the upper Stark levels of the ground-state manifold. This happens because the energy separation between the ground state and the vibrational states of the manifold is comparable to the thermal quantum of energy $E_t = k_b T \simeq 25\ \text{meV}$ at room temperature (being $k_b = 1.38 \cdot 10^{-23}\ \text{J/K}$ the Boltzmann constant and T the absolute temperature, conventionally considered 300 K at room temperature). This leads to an increased lasing threshold, especially for "short"-wavelength transitions.

Nevertheless, Yb-doped quasi-three-level materials offer a number of advantages: minimal excited-state absorption, absence of up-conversion and cross-relaxation processes, high quantum efficiency, low quantum defect (reduced thermal load), and in many hosts a broad emission bandwidth, well suited to ultrashort pulse generation or amplification.

Yb^{3+} ions feature a relatively simple electronic structure (see Fig. 2.1) with only two multiplets involved in lasing transitions: the ground-state $^2F_{7/2}$ and the excited state $^2F_{5/2}$ manifolds [8]. These manifolds are split into Stark sublevels due to the crystal field. The

laser transition typically involves the lowest Stark level of the excited state and higher-lying levels of the ground state.

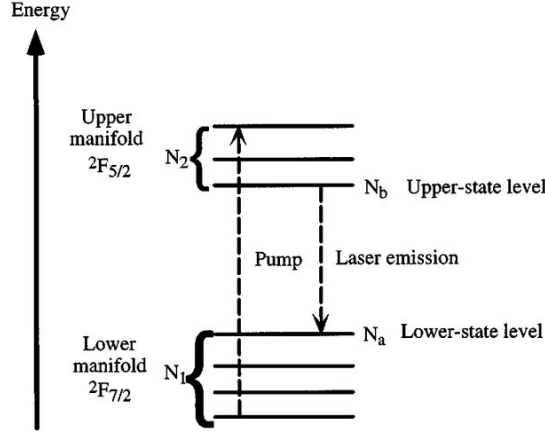


FIGURE 2.1: Jablonski diagram laser transition for a typical Yb^{3+} -doped Quasi-3 level laser material [9].

At room temperature, thermal population persists even in the higher sublevels of the ground-state manifold, leading to reabsorption losses. This behavior is a distinctive feature of quasi-three-level (Q3L) laser systems such as $\text{Yb}:\text{YAG}$. However, if the crystal is cooled to cryogenic temperatures, the population in the upper sublevels of the ground state becomes negligible, effectively eliminating reabsorption [10]. Under these conditions, the system behaves like a true four-level laser (Fig. 2.2, right).

The main drawbacks of this class of materials are the following:

- When employed as active media for oscillators, the gain must overcome intrinsic losses due to reabsorption, which normally dominate the total cavity losses. For this reason the pump intensity required to reach the threshold is much higher with respect to a classical four-level laser material. This is the main reason why the development of Yb -doped lasers have been possible only after crucial technological improvements in InGaAs laser diodes for originally exploited in telecom applications.
- When employed as active media for amplifiers, gain saturation and bleaching can be strongly dependent on the spatial overlap between pump and signal beams.

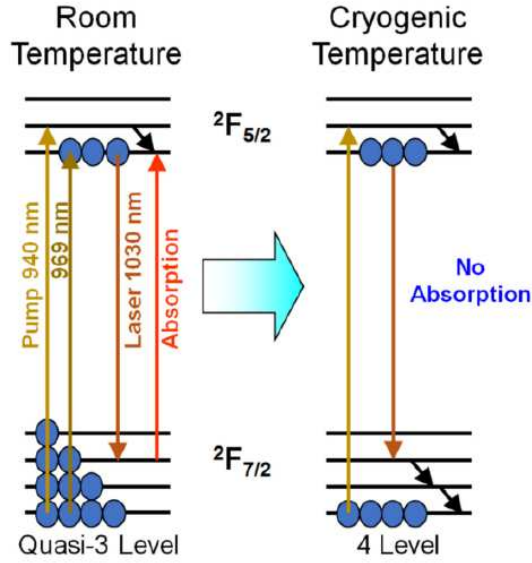


FIGURE 2.2: Atomic transition of Yb:YAG: on the left at room temperature and, on the right, at cryogenic temperature [11]

- Due to the high pump intensity required with quasi-three level materials, saturation of pump absorption, which is typically negligible in 4-level systems, is a significant effect not only in fiber lasers, but even in bulk Yb-doped lasers. This makes pump absorption depend on the incoming signal intensity in amplifiers and on output coupling rate in oscillators, and this effect can not be overlooked during the design of oscillators/amplifiers based on this class of active media.

2.1 Active Medium Choice

As discussed in the Introduction, one of the primary goals of this thesis was the development of a compact and efficient, high-gain pre-amplifier stage. In order to achieve high gain over a limited number of passes, the active medium must be capable of efficiently absorbing tightly focused pump light from high-brightness sources such as tapered diodes. This requirement implies the need for a short crystal with a high doping concentration, ensuring strong absorption over the limited propagation length available. Moreover, the peculiar characteristic of the MiFem module is to accommodate two polarization-coupled

tapered laser diodes. Therefore, the resulting pump beam is made by the spatial superposition of two linearly, orthogonally polarized, laser beams. For this reason, isotropic gain media could immediately simplify the design of the amplifier, since pump absorption would be independent on the polarization. Among such materials, Yb:YAG is the most prominent, offering high thermal conductivity and a relatively high emission cross section. However, as discussed in Section 2.3, the peak of Yb:YAG absorption spectrum lies far from the emission wavelength of the tapered diodes employed in our setup (978 nm), making Yb:YAG unsuitable for this specific application.

Another well-known, isotropic Yb-doped crystal is Yb:CaF₂, but despite possessing a very broad emission cross section and an absorption peak at around 976 nm, this material has a relatively low peak value of both the absorption and emission cross section (see Section 2.3), thus making it unsuitable for a compact, high-gain preamplifier.

In the last 15-20 years a lot of very promising Yb-doped crystals capable of generating and amplifying ultrashort pulses even with pulse duration < 100 fs have been proposed [8, 12, 13, 14, 15]. However, up to now, only a few of them have made the jump from the laser-material development stage of lab-samples to the stage of commercially-available laser crystals. Indeed, a lot of factors that are quite usually overlooked at the initial stage of the development of a new laser material, become crucial when a promising material has to undergo the different phases of industrial-grade qualification.

To identify viable alternatives, we surveyed various commercial suppliers of laser crystals, summarized in Table 2.1. The most readily available materials include Yb:YAG and the potassium tungstates Yb:KGW and Yb:KYW. While "newer" materials such as Yb:CALGO have emerged in the market and are offered by some suppliers (see Table 2.1), their availability has significantly increased only in the last 5 years, making them less established in commercial products.

After evaluating the trade-offs, the best solution was found to be the use of two highly doped Yb:KYW crystals arranged in a crossed configuration. Yb:KYW, being a biaxial crystal, exhibits strong birefringence and anisotropic absorption and emission properties. This anisotropy can be effectively exploited to match the polarization of each diode with

the optimal crystallographic axis of each crystal.

Preliminary tests conducted with a single Yb:KYW crystal pumped by one tapered diode demonstrated promising results, as reported in [16]. For better clarity, the most significant results obtained in this configuration are also briefly summarized in Chapter 3.

Encouraged by these results, we proceeded with a double crystal amplifier design, where each crystal was oriented to align its Nm-axis, offering to the highest absorption cross section, with the polarization of the respective diode. As shown in Section 2.4, the absorption cross section along the Nm axis is significantly larger than along the Np axis, allowing each diode to be efficiently absorbed by its corresponding crystal.

By carefully managing the polarization of the pump beams and the orientation of the crystals, high absorption efficiency and large gain per pass were achieved. The results of the final Yb:KYW amplifier implementation are detailed in Chapter 3.

Following the above-mentioned considerations, it is evident that the same Yb:KYW crystal employed in the amplifier stage is not ideal for use in a mode-locked oscillator, particularly if the goal is to fully exploit the available pump power from both diodes. Due to its strong birefringence and polarization-dependent absorption, using both diodes simultaneously in a single-crystal oscillator configuration would result in inefficient pump absorption.

Alternatively, a more effective strategy is to use either an isotropic material that exhibits strong absorption around 978 nm, or a material which exhibits similar absorption cross section for both the polarization at around the available pump wavelength. At the Laser Source Laboratory of the University of Pavia, two Yb:CaF₂ samples were available, as they were used in the past in experiments of generation of femtosecond pulses in diode-pumped oscillators [17]. The most relevant characteristics and spectroscopic properties of Yb:CaF₂ are summarized in section 2.5.

Among birefringent fluoride crystals, a promising candidate is Yb:YLF (and its isomorph counterpart Yb:LLF). Although it is a birefringent uniaxial crystal, as discussed in Section 2.6, the absorption cross section at 978 nm for the two orthogonal polarizations

are nearly identical. This makes Yb:YLF/LLF a practical option for a compact femtosecond oscillator pumped by polarization-coupled tapered diodes. The preliminary experimental results obtained in cw regime and SESAM mode-locking employing Yb:CaF₂ and Yb:YLF samples already available in the lab and pumped by the available MiFem module are presented and discussed in Chapter 4.

Supplier	Yb:YAG	Yb:KYW-KGW	Yb:CALGO	Yb:YLF	Yb:CaF ₂
EKSMA Optics [18]	✗	✓	✓	✗	✗
OPTOGAMA [19]	✓	✓	✓	✓	✓
CASTECH Inc. [20]	✓	✓	✓	✓	✓
Altechna [21]	✓	✗	✗	✗	✗
OptoCity [22]	✓	✓	✗	✗	✗

TABLE 2.1: Main suppliers of Yb-doped laser crystals and available materials

2.2 Gain Cross-Section in Quasi-Three-Level Materials

The main difference between quasi-three-level (Q3L) materials and four-level systems is that, in Q3L materials, the absorption and emission cross-sections are partially overlapping over a large part of the spectrum. This causes the shape of the effective cross-section, and therefore the gain, to strongly depend on the population inversion present in the active medium.

The population inversion parameter β is defined as:

$$\beta = \frac{N_2}{N_1 + N_2} = \frac{N_2}{N_{\text{tot}}}, \quad (2.1)$$

where $N_{\text{tot}} = N_1 + N_2$ is determined by the concentration of active ions, i.e., by the doping level.

2.2.1 Amplifier

In an amplifier, β is a pump-dependent parameter that, depending on the incident pump power, defines the shape of the effective cross-section:

$$\sigma_{\text{eff}}(\lambda) = \beta \sigma_e(\lambda) - [1 - \beta] \sigma_a(\lambda). \quad (2.2)$$

Notice that when $\beta \rightarrow 1$, the effective cross-section $\sigma_{\text{eff}}(\lambda)$ approaches the emission cross-section $\sigma_e(\lambda)$. Instead, $\sigma_a(\lambda)$ represents the absorption cross-section.

Figure 2.3 shows an example of how, as β increases, the effective cross-section progressively resembles the emission cross-section. Since a strong population inversion is typically generated in amplifiers, β is usually relatively high, which is not the case for femtosecond oscillators, where its value is typically of the order of the output coupling losses, hence few percent.

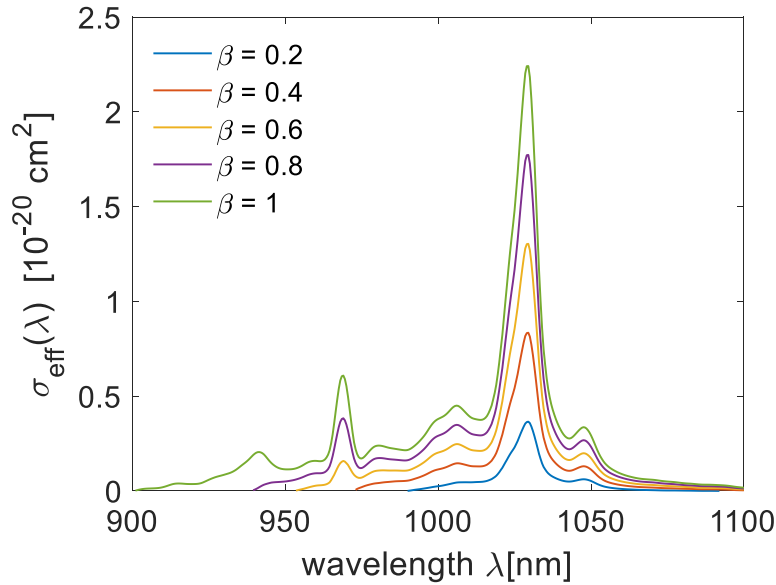


FIGURE 2.3: Effective cross-section of Yb:YAG for different values of β .

A more illustrative example of the strong dependence of the effective cross section on the parameter β is shown in Fig. 2.4. In this case, the active medium is Yb:KYW, the same material used in our amplification experiment (see Chapter 3). In high-gain amplifiers, the pump intensity is typically high, resulting in a β value significantly larger with respect to the case of oscillators and easily $> 0.2 - 0.4$. As it can be seen, as β increases the effective gain cross section becomes more and more peaked around ~ 1025 nm for the Nm axis and 1040 nm for Np, approaching the shape of the emission cross

section ($\beta = 1$).

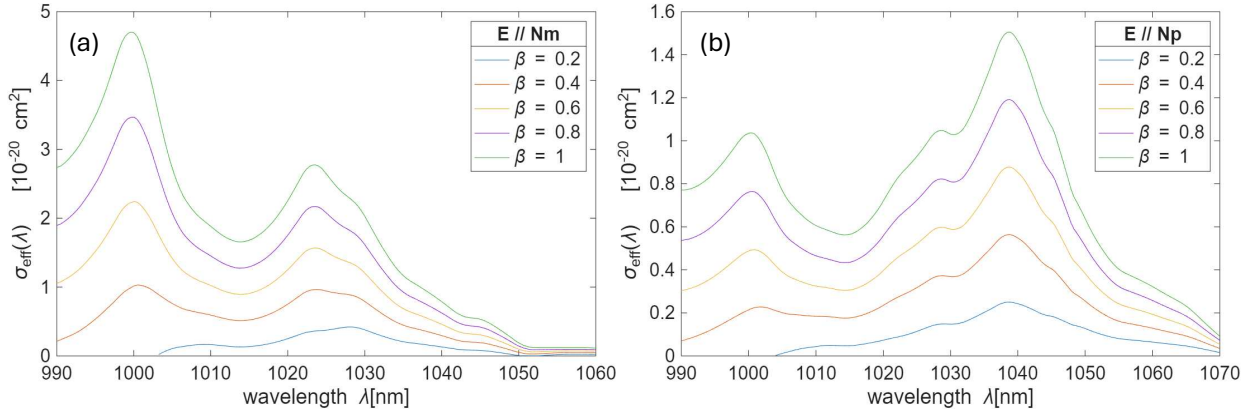


FIGURE 2.4: Effective cross-section of Yb:KYW for different values of β : (a) $E \parallel N_m$ and (b) $E \parallel N_p$

2.2.2 Laser oscillator

In quasi-three-level laser materials, reabsorption losses at the lasing wavelength cannot be neglected. The effective gain depends on the steady-state population inversion, which is fixed at the laser threshold. In general, the gain threshold condition can be written as:

$$g_{\text{th}}(\lambda) = 2L_g [N_2\sigma_e(\lambda) - N_1\sigma_a(\lambda)] = -\ln(R_{\text{oc}}) + \ell_c, \quad (2.3)$$

where the right-hand term represents the total round-trip losses, including the output coupling loss $-\ln(R_{\text{oc}})$ and the residual cavity losses ℓ_c . The left-hand term, on the other hand, incorporates both stimulated emission and reabsorption contributions. If the mirror reflectivity spectra are sufficiently flat, the output coupling and residual losses can reasonably be assumed to be wavelength-independent, as is commonly the case in practical resonators.

The expression above can be conveniently reformulated by substituting 2.1:

$$g_{\text{th}} = -\ln(R_{\text{oc}}) + \ell_c = 2L_g N_{\text{tot}} \{ \beta [\sigma_e(\lambda) + \sigma_a(\lambda)] - \sigma_a(\lambda) \}. \quad (2.4)$$

This equation can be rearranged to express the inversion factor $\beta(\lambda)$ required to reach the lasing threshold at each wavelength. Consequently, the lasing wavelength λ_L corresponds to the minimum of $\beta(\lambda)$, once R_{oc} and ℓ_c are specified.

Carrying out the derivation yields:

$$\beta(\lambda) = \frac{\sigma_a(\lambda)}{\sigma_e(\lambda) + \sigma_a(\lambda)} + \frac{-\ln(R_{oc}) + \ell_c}{2L_g N_{tot} [\sigma_e(\lambda) + \sigma_a(\lambda)]}. \quad (2.5)$$

It is worth noting that, in the special case of a purely four-level system ($\sigma_a = 0$), this relation simplifies to:

$$g_{th} = 2L_g \sigma_e N_2 = -\ln(R_{oc}) + \ell_c. \quad (2.6)$$

Once the steady-state inversion at threshold $\beta_{th} = \min\{\beta(\lambda)\}$ is reached, the effective gain cross section can be defined as:

$$\sigma_{eff}(\lambda) = \beta_{th} \sigma_e(\lambda) - [1 - \beta_{th}] \sigma_a(\lambda). \quad (2.7)$$

Finally, after determining β and the lasing wavelength, the reabsorption losses can be expressed as:

$$\ell_a(\lambda_L) = 2L_g N_{tot} \sigma_a(\lambda_L) [1 - \beta]. \quad (2.8)$$

Examples of effective cross sections found in the literature for Yb:CaF₂ and Yb:YLF—the materials employed in our oscillator experiments—can be found in [23] and [24], respectively.

2.3 Yb:YAG (Yttrium Aluminum Garnet)

Yb:YAG is one of the most mature and widely adopted Yb-doped materials. YAG crystal matrix is cubic (hence isotropic) and offers high mechanical robustness, chemical stability, and thermal conductivity in the range of 7–10 W/m·K [25], which enables operation at high average powers [26]. However, its emission bandwidth is relatively narrow (~ 8

nm), limiting its application in sub-300 fs pulse generation [27] unless additional external spectral broadening is introduced.

Typical applications include thin-disk oscillators and multi-pass amplifiers, where high pump absorption, good beam quality, and thermal handling are paramount. Output powers exceeding 1 kW in CW or hundreds of watts in ultrafast regimes have been demonstrated [28].

The absorption and emission cross section of Yb:YAG [29] are shown in Fig. 2.5. The main absorption peak occurs around 940 nm (see red curve in 2.5). This is the most common pumping wavelength for Yb:YAG also thanks to the reasonably wide absorption bandwidth around 940 nm, which permits to significantly simplify the thermal control of the pump diodes, which is a huge benefit in high average power applications. Notably, there exists a specific wavelength, 969 nm, where the absorption and emission cross sections are equal. This transition is referred to as the "zero-phonon line," as it connects the ground-state sub-level directly with the lowest sub-level of the excited-state manifold without phonon interaction. The peak emission cross-section $\sigma_e \sim 2.2 \cdot 10^{-20} \text{ cm}^2$ is one of the highest among Yb-doped materials.

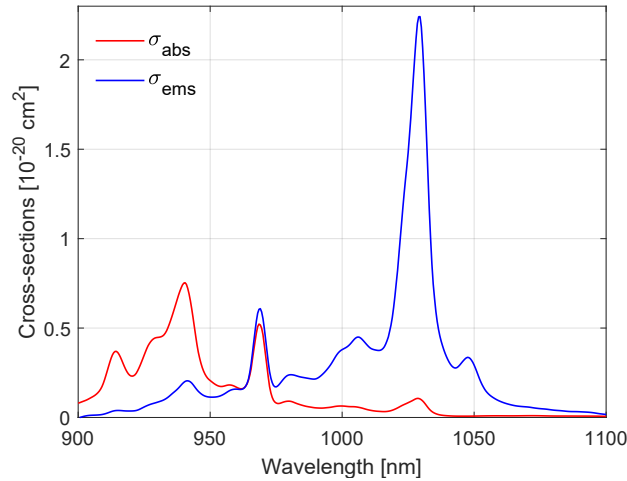


FIGURE 2.5: Absorption and emission cross-sections of Yb:YAG

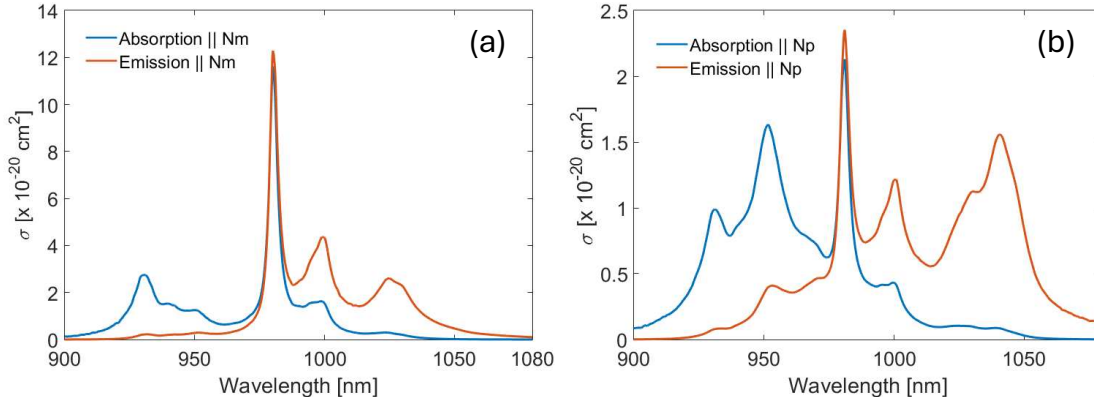
2.4 Yb:KYW (Potassium Yttrium Tungstate)

Ytterbium-doped potassium yttrium tungstate ($\text{Yb}^{3+}:\text{KY}(\text{WO}_4)_2$), commonly referred to as Yb:KYW, is among the most widely employed gain media for the generation of ultrashort pulses in the femtosecond regime around $1\ \mu\text{m}$. This crystal is biaxial, exhibiting significant birefringence and a pronounced gain anisotropy that must be carefully considered when designing laser systems. The optical properties of Yb:KYW strongly depend on the polarization of the interacting light relative to the crystal principal optical axes commonly denoted as N_m , N_p , and N_g . These axes are associated with the distinct refractive indices along different crystallographic directions, leading to highly polarization-dependent absorption and emission behaviors.

The crystal spectroscopic characteristics are particularly favorable for ultrafast laser applications. A key feature of Yb:KYW is its relatively broad emission spectrum, which typically spans 20 nm (FWHM), enabling the generation of pulses with durations below 100 fs exploiting the larger bandwidth of the N_p -axis[30][31]. Thanks to these properties Yb:KYW thin disk, regenerative multi pass amplifier work was demonstrated in literature, varying from to 300 fs [32] to sub-ps [33] achieving pulse energy between μJ to hundreds of μJ (or even more).

The highest values of absorption and emission cross sections are achieved when the electric field of the light is aligned parallel to the N_m axis ($E \parallel N_m$). When the laser beam propagates along the N_g axis—a configuration referred to as the N_g -cut—the polarization can be aligned with either the N_m or N_p axis, depending on the desired operational characteristics. The N_m orientation is generally preferred due to its superior cross-section values. At the typical diode pump wavelength of 980 nm, the absorption cross section reaches approximately $\sigma_a \simeq 13 \times 10^{-20}\ \text{cm}^2$, while the emission cross section peaks at $\sigma_e \simeq 3 \times 10^{-20}\ \text{cm}^2$ near 1023 nm [31], as illustrated in Figure 2.6 (a).

Alternatively, when the polarization is aligned parallel to the N_p axis ($E \parallel N_p$), the corresponding cross sections are significantly lower, with typical values of $\sigma_a \simeq 2 \times 10^{-20}\ \text{cm}^2$ at 980 nm for absorption, and $\sigma_e \simeq 1.5 \times 10^{-20}\ \text{cm}^2$ at 1040 nm [31] for emission (see Figure 2.6(b)).

FIGURE 2.6: Yb:KYW cross-section: (a) $E \parallel N_m$ and (b) $E \parallel N_p$

Despite its relatively modest thermal conductivity —on the order of $3 \text{ W/m}\cdot\text{K}$ [34]— Yb:KYW can be effectively employed in moderate-power systems provided that appropriate thermal management strategies are implemented. Its high quantum efficiency, combined with low quantum defect and reduced parasitic losses, allows for stable and efficient operation even under diode-pumped conditions. The intrinsic birefringence of the crystal also serves to mitigate thermally induced depolarization losses, which can otherwise degrade beam quality in high-power lasers.

Moreover, Yb:KYW excellent spectroscopic features make it particularly well-suited for diode pumping, with strong absorption peaks not only around 979 nm (zero phonon line) but also near 946 nm. These characteristics have led to its successful implementation in a wide range of femtosecond laser architectures, including dispersion-compensated resonators with prisms, as well as compact mode-locked oscillators based on Kerr-lens or saturable absorber mechanisms.

In summary, Yb:KYW combines broad emission bandwidth, favorable diode-pump compatibility, and beneficial anisotropic optical properties, making it an outstanding choice for high-performance femtosecond laser sources, and the best choice for our high gain pre-amplifier (see Chapter 3).

2.5 Yb:CaF₂ (Calcium Fluoride)

Yb:CaF₂ is a well-known active medium for ultrashort pulse lasers. This material has played a key role since the early development of femtosecond Yb-based systems, primarily because high-quality CaF₂ crystals can be grown reliably. Its intrinsically low group velocity dispersion, high transparency in the near-infrared, and excellent optical quality make it an ideal host for broadband amplification. Furthermore, Yb:CaF₂ offers an extraordinarily wide emission bandwidth[35].

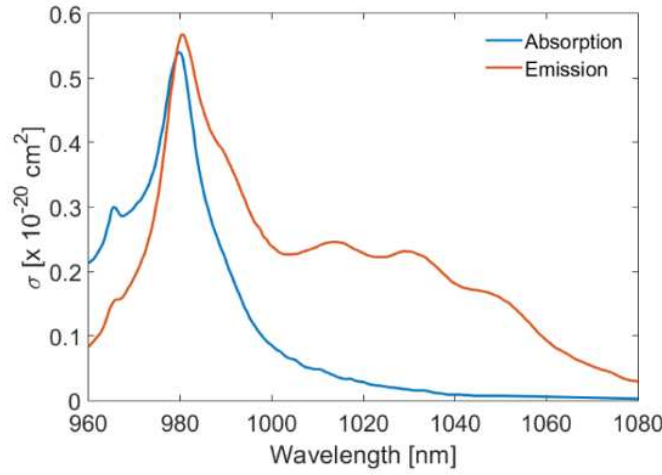


FIGURE 2.7: Absorption and emission cross-sections of Yb:CaF₂

The crystal is cubic and isotropic, similar to YAG, but suffers from lower thermal conductivity, mainly at high doping level concentration (2–3 W/m·K) [36] and higher fragility, making it challenging to handle in high-average-power systems. However, thanks to the wide spectrum, Yb:CaF₂ can generate sub-60 fs pulses [17] and even shorter such as 50 fs [37] pulses. This crystal can also be employed in Kerr-lens mode-locked (KLM) lasers; however, its relatively low nonlinear refractive index, $n_2 \sim 1.1 \times 10^{-20} \text{ m}^2/\text{W}$ [38], makes the self-focusing effect weak and therefore renders KLM operation more challenging to achieve.

Applications include front-ends for optical parametric chirped-pulse amplification (OPCPA), carrier-envelope phase-stable oscillators, and broadband ultrafast systems [39]. The cross sections are reported in Figure 2.7: The zero-phonon peak absorption is at the

corresponding 980 nm with a maximum value of $\sigma \simeq 0.55 \times 10^{-20} \text{ cm}^2$, similar to Yb:YAG (Figure 2.5) and lower than the Np Yb:KYW absorption cross section (Figure 2.6 (b) cross-sections), making this material not ideal for the high gain amplifier.

2.6 Yb:YLF (Yttrium Lithium Fluoride)

Ytterbium-doped lithium yttrium fluoride (Yb:YLF) is a uniaxial, birefringent crystal belonging to the tetragonal crystal system. It has gained significance due to its favorable spectroscopic and thermal properties. Yb:YLF supports multiple lasing transitions. Depending on the population inversion condition, the emission wavelength can range from 1050 nm to 1040 nm, while at higher inversion levels the lasing shifts further toward the peak of the emission cross-section, reaching 1020 nm. This behavior is observed for both π -polarization (electric field parallel to the optical axis) and σ -polarization (electric field perpendicular to the optical axis) [40, 24].

These transitions exhibit moderate emission cross-sections of approximately $\sigma_e \sim 10^{-21} \text{ cm}^2$ for both polarization states (see Figure 2.8(b)). The gain bandwidth spans roughly 15–20 nm, which allows for the generation of pulses as short as 100 fs [41]. Moreover an innovative recent work with a particular design of highly doped Yb:YLF allowed the shortest ever pulse duration of 40 fs, with 300 mW, 100 MHz was demonstrated [42]. Under high inversion or strong output coupling conditions, lasing near 1020 nm is also possible, although less commonly utilized [40][43].

The absorption band of Yb:YLF is centered near 960 nm, but the peak value of the absorption cross section in this spectral region is markedly different for the two axes, and namely, $\sigma_a \sim 10 \times 10^{-21} \text{ cm}^2$ ($E // c$) and $\sigma_a \sim 4 \times 10^{-21} \text{ cm}^2$ ($E \perp c$). Around 976–978 nm, the absorption cross-sections is smaller (around $2.5 \times 10^{-21} \text{ cm}^2$), but very similar for the two polarization states (see inset of Figure 2.8(a)) [24], allowing efficient pumping with unpolarized diodes or polarization-combined diode modules (e.g. MiFem module discussed in Chapter 1).

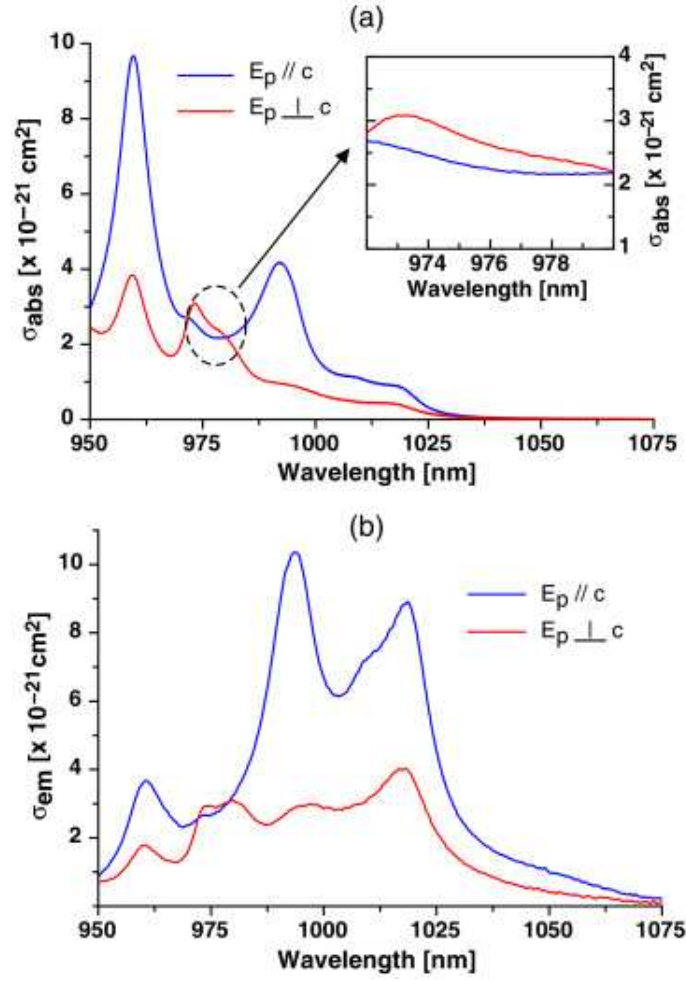


FIGURE 2.8: (a) Absorption cross-section of Yb:YLF for both polarizations of the pump beam. The inset shows a zoom around 976 nm. (b) Emission cross-section for both polarizations [24].

The fluorescence lifetime of Yb:YLF is typically around $\tau_f \sim 2$ ms, enabling efficient energy storage, which is advantageous for high-energy Q-switched (QS) pulse generation [44].

Despite its relatively low thermal conductivity (about 4–6 W/m·K), Yb:YLF can handle moderate average powers with manageable thermal lensing, especially under cryogenic conditions [45]. Its low nonlinear refractive index ($n_2 \sim 1.1 \times 10^{-20} \text{ m}^2/\text{W}$), similar to Yb:CaF₂, makes it less suitable for Kerr-lens mode-locking (KLM).

One of the key advantages of Yb:YLF is its birefringence, which spectrally separates

the polarization components. This aids in gain shaping, polarization control, and preservation of the polarization state during amplification, an essential characteristic in systems requiring high-polarization extinction ratios. In amplification stages, particularly under cryogenic cooling, regenerative Yb:YLF systems have demonstrated output powers exceeding 100 W at 10 kHz repetition rate and continuous-wave (CW) operation above 400 W has also been reported [45]. These features—combined with minimal parasitic losses, and excellent optical quality—make Yb:YLF an ideal gain medium for high-contrast ultrafast systems, front ends for OPCPA, and carrier-envelope phase (CEP) stable sources [46].

2.7 Summary

Quasi-three-level Yb-doped materials constitute the backbone of many state-of-the-art laser systems, particularly in the near-infrared region. While Yb:YAG remains the workhorse of high-power laser applications owing to its favorable thermal conductivity, high doping tolerance, and well-established crystal growth techniques, emerging Yb-doped hosts such as Yb:KYW, Yb:YLF, and Yb:CaF₂ have opened new avenues in ultrafast and spectrally agile laser systems. These newer materials exhibit properties that are particularly advantageous for femtosecond pulse generation, gain shaping, and precise polarization control, making them well suited for applications such as frequency combs, high-harmonic generation, and front ends for OPCPA systems.

The selection of a gain medium in this class of lasers is rarely governed by a single parameter. Instead, it requires a careful balance among several interrelated factors: gain bandwidth (which determines the shortest achievable pulse duration), emission cross-section (which influences gain efficiency and saturation behavior), thermal and mechanical properties (critical for power scaling and beam quality), and birefringence (relevant for pulse shaping, noise suppression, non linear process, and system integration).

Moreover, the quasi-three-level nature of Yb-doped systems presents specific challenges such as ground state absorption at the laser wavelength and the need for efficient

heat removal. When properly optimized in terms of pump geometry, doping concentration, and thermal management, these systems can deliver both industrial-grade reliability and cutting-edge performance in the sub-100 fs regime.

Table 2.2 summarizes the main characteristics of the aforementioned Yb-doped crystals presented in this Chapter, offering a comparative overview of their suitability for different application domains ranging from high-average-power industrial platforms to ultrafast scientific instrumentation.

TABLE 2.2: Key properties and typical performance of Yb-doped quasi-3-level materials.

Material	Yb:YAG	Yb:KYW	Yb:YLF	Yb:CaF ₂
Emission Band. FWHM	~ 10 nm	~ 20 nm	~ 20 nm	~ 40 nm
Thermal Cond. (Wm⁻¹K⁻¹)	7-10	~ 3	~ 4	2-3
Crystal structure	Cubic	Biaxial	Uniaxial	Cubic
Pulse Duration	< 300 fs	< 100 fs	< 100 fs	< 50 fs

Chapter 3

Amplification experiments

3.1 The fs laser seeder

For the amplification experiments in Pavia we employed a Yb:KYW-based fs-laser used in previous experiments and already available in the laboratory. The laser oscillator was built in a way that it could be quite easily switched from continuous wave to mode-locking regime by replacing the HR end mirror with the saturable absorber mirrors (SAM) (see Fig.3.1). Thanks to the single prism configuration[47], the laser output wavelength could be easily tuned around 1030 nm in both regimes. The resonator was designed as an X-shaped cavity with several folding mirrors to maintain the footprint reasonably compact. The cavity was pumped with a 6-W fiber coupled laser diode (NA = 0.22, fiber core diameter 105 μm) at 976 nm (see figure 3.1). The diode is coupled in a short fiber, so that, despite the fiber being multi-mode, the diode polarization is well preserved. The employed active medium was a 5%-doped, 2-mm-long, Ng-cut, Yb:KYW crystal and the pump diode polarization was aligned to the crystal Nm-axis.

As shown in Figure 3.2 in CW operation, the laser delivered a maximum output power of 850 mW at 1030 nm for an absorbed pump power of 4 W. The corresponding slope efficiency was 28%, with a threshold absorbed pump power of ~ 280 mW.

The relatively modest slope efficiency can be attributed to the relatively low output coupler transmission ($T_{oc} = 3\%$) that was chosen to enhance the central wavelength tuning range in both CW and ML experiments. Indeed, the oscillator demonstrated a tuning

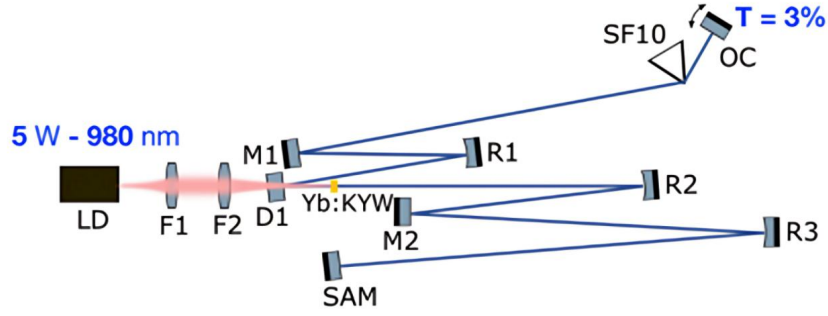


FIGURE 3.1: Yb:KYW Seeder Setup. M1, M2: High reflectivity (HR) flat mirror at 1000-1100 nm; R1: $r = 150$ mm spherical mirror ; R2: $r = 400$ mm spherical mirror, R3: $r = 500$ mm spherical mirror ; D1: Dichroic Mirror (DM) High Transmittivity (HT) at 980 nm and HR at 1000-1100 nm; OC: Output coupling mirror $T = 3\%$. Distances: R1-R2 = 280 mm; R2-R3 = 430 mm; R3-SAM=250 mm; R1-OC = 370 mm.

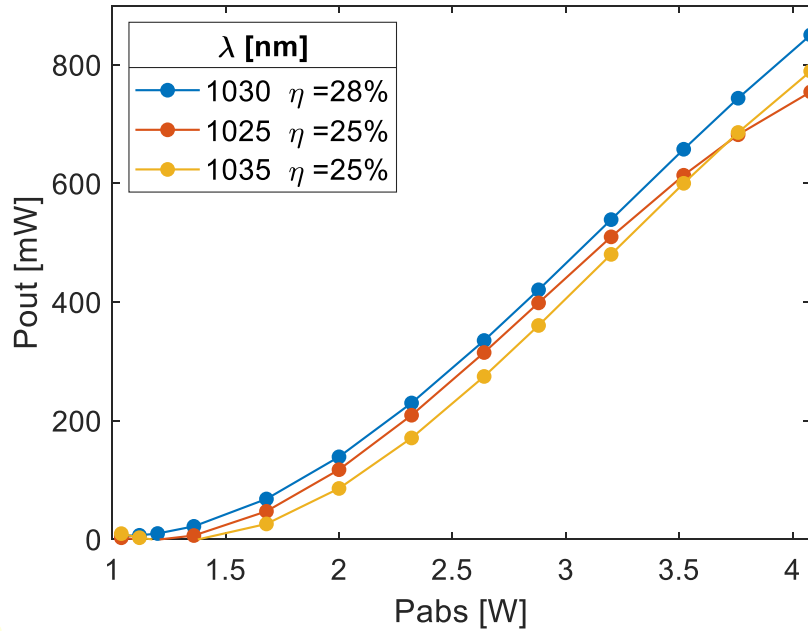


FIGURE 3.2: Yb:KYW Seeder CW output power vs. absorbed pump power at different wavelength. Data are shown in detail for 1030, 1025, 1035 nm

range from 1020 to 1050 nm by adjusting the output coupler, confirming its versatility as a broadband seeding source (see Fig. 3.3).

Stable mode-locking was obtained by replacing the HR end mirror with a SESAM. In this regime, the oscillator operated at a repetition rate of 113 MHz, delivering up to 650 mW of average power with the $T = 3\%$ output coupler.

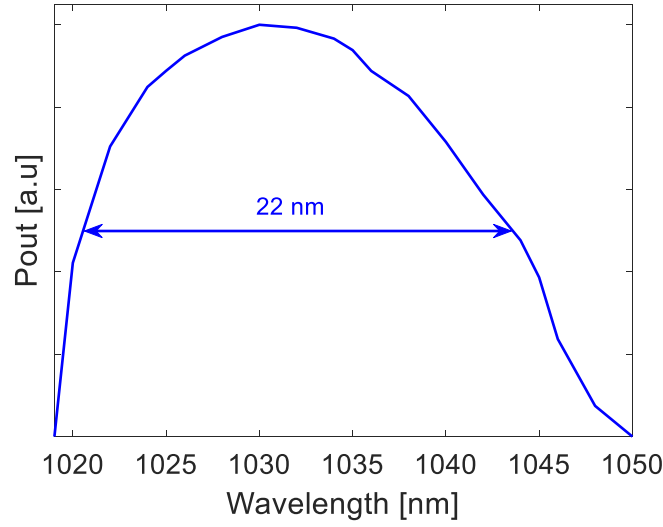


FIGURE 3.3: CW tuning range of the Yb:KYW seeder.

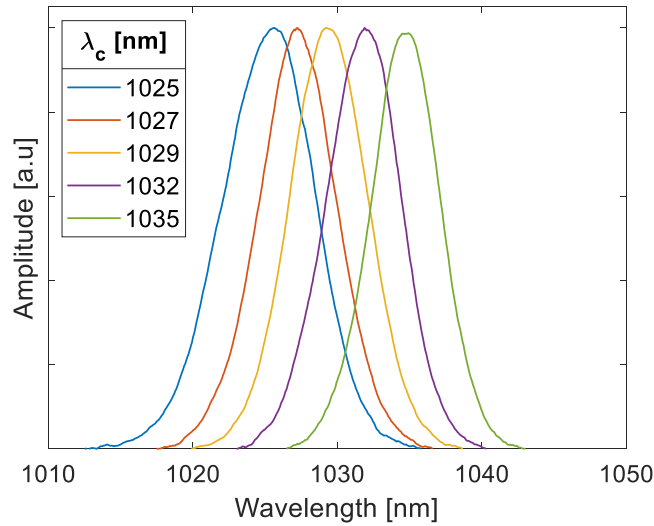


FIGURE 3.4: Typical spectra of the Yb:KYW seeder within the tuning range 1025–1035 nm.

The femtosecond regime central output wavelength was tuneable from 1025 to 1035 nm (Fig. 3.4). Across this spectral range, the laser consistently produced pulses with duration below 300 fs and was very stable. Shorter pulses, down to less than 200 fs, could be achieved by optimizing intracavity dispersion; however, this reduced the long-term stability of the mode-locking regime. For subsequent amplification experiments, the more stable condition with slightly longer pulses was preferred.

An example of the measured autocorrelation trace and the corresponding optical

spectrum at 1026 nm is reported in Fig. 3.5. A summary of the pulse durations, spectral bandwidths, and corresponding time–bandwidth products over the tuning range is given in Table 3.1.

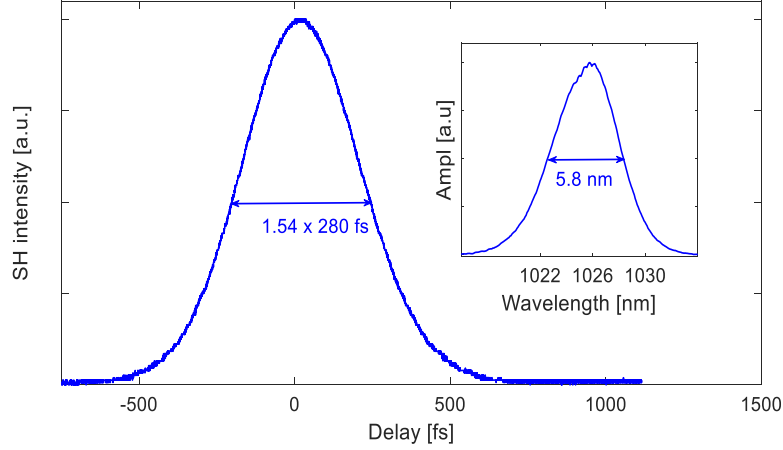


FIGURE 3.5: Autocorrelation trace of the Yb:KYW seeder at 1026 nm. The corresponding optical spectrum is shown in the inset.

TABLE 3.1: Pulse duration, spectral bandwidth and time bandwidth product of the Yb:KYW seeder.

Wavelength [nm]	Pulse duration [fs]	Spectrum FWHM [nm]	TBP
1026	280	5.8	0.41
1029	271	5.2	0.36
1035	235	5.9	0.40

3.2 Preliminary results obtained with a Single-Crystal, Single-Tapered-Diode Amplifier

3.2.1 Design Strategy

In this section I summarize the design strategy and the main results I achieved during my Master thesis research activity and at the very beginning of my PhD. Even if the bulk of these experiments were done before the beginning of my PhD, and were already reported in my Master thesis dissertation, they are relevant to understand the activity I

actually carried out later, so I briefly present them here. At the beginning of my activity I had at my disposal a tapered-diode pump module with a single diode emitting a power of 5 W with high beam quality, as described in Chapter 2. The main experimental goal was the demonstration that the high brilliance of the tapered diode could be exploited to maximize the gain per Watt of absorbed pump power in a compact single or double-pass amplifier. Indeed, the high spatial beam quality of the pump beam allowed to tightly focus the pump (to maximize small signal gain), but with a corresponding almost diffraction-limited pump beam confocal parameter. This permits to distribute the absorption of the pump over a reasonable crystal length still maintaining a good spatial overlap with a diffraction limited and waist-matched seed beam. The design of such an amplifier is not trivial, because strong pump focusing leads to very high pump intensity, that can significantly exceed the saturation intensity at the pump wavelength. One of the consequences is that to permit a sufficient pump absorption in a short crystal under very high pump intensity, high doping concentration is required. In our experiments we used a 9.5% at. Yb-doped, 3-mm-long Ng-cut KYW crystal. Details about the design of the amplifier are reported in [16]. For better clarity I report in Fig. 3.6 the single-pass amplification setup.

Among the crystals available in the laboratory, a 3-mm-long, 9.5% doped, Ng-cut Yb:KYW sample was chosen as the best candidate for this configuration. We set the pump beam waist to $w_p \approx 25 \mu\text{m}$, in order to maintain the pump beam confocal parameter b reasonably longer than the crystal length. Indeed, given the definition of b in Eq. 3.1 where the refractive index $n = 2$ and the pump beam quality factor $M_p^2 = 1.5$, the confocal parameter b of the pump beam fairly is:

$$b = \frac{2\pi w_p^2 n}{\lambda_p M_p^2} \approx 4.5 \text{ mm} \quad (3.1)$$

To evaluate pump absorption saturation, the incident pump intensity must be compared with the saturation intensity of the active medium. From the known cross-sections (Fig. 2.6), with $\sigma_a \approx \sigma_e \approx 1 \times 10^{-19} \text{ cm}^2$ at 980 nm and a fluorescence lifetime $\tau_f \approx 350 \mu\text{s}$, the pump saturation intensity is:

$$I_{SP} = \frac{hc/\lambda_p}{(\sigma_a + \sigma_e) \cdot \tau_f} \approx 3 \text{ kW/cm}^2 \quad (3.2)$$

In our setup, for an incident pump power $P_p = 5 \text{ W}$ focused to a $w_p = 25 \mu\text{m}$ waist, the calculated pump intensity is:

$$I_p = \frac{P_p}{\pi w_p^2} \approx 250 \text{ kW/cm}^2 \quad (3.3)$$

thus confirming that the amplifier operates well above the saturation regime.

To match the tight pump waist, the seed beam must also be shaped accordingly to maintain a good overlap along the whole crystal length. This was done by matching the seed and pump beam waist and radius of curvature over the focusing lens (ACR in Fig. 3.6). This was realized adjusting a 1:1 telescope placed along the seed beam path, before the Faraday isolator, and not shown in Fig. 3.6.

3.2.2 Single-Pass Amplification results

The pump module was single-tapered-diode, providing a linearly polarized beam. In order to control the incident pump power without changing the driving current of the tapered diode (which affects also the spatial characteristics of the pump beam), we employed a half-wave-plate in combination with a polarizing beam cube. At the maximum drive current of 8.5 A, and accounting for residual losses in the optics, the maximum pump power delivered to the active medium was 4.25 W. The seeder was initially kept in CW operation mode.

A dichroic mirror positioned after the crystal make it possible to measure the transmitted pump power under different seeder power levels, and avoided dangerous back reflections of the pump. The measurements showed that by increasing the seed power from 20 mW to 600 mW, the absorbed pump fraction increased from 55% to 75% (Table 3.2), demonstrating the significant role of saturation in pump absorption. In this sense, a multi-pass configuration would enhance pump absorption especially when we inject low input seeder power.

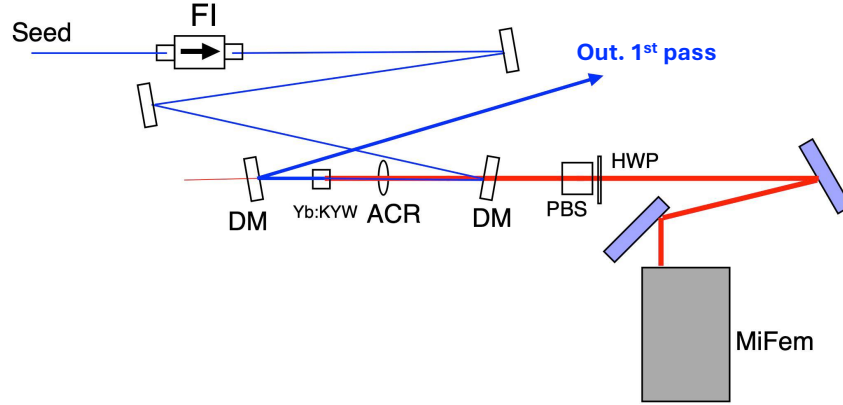


FIGURE 3.6: Single pass experiment setup:FI: Faraday Isolator 93% transmittivity; DM: Dichroic Mirror High Transmittivity (HT) at 980 nm and HR at 1000-1100 nm; Yb:KYW: Ng-cut, 3 mm, 9.5%; ACR: Achromatic lens $f = 25$ mm, PBS: Polarized Beam Splitter; HWP: Half-Wave-Plate

P_{inc} [W]	P_{tr} [W] @ 600 mW	P_{abs} [W] @ 600 mW	P_{tr} [W] @ 20 mW	P_{abs} [W] @ 20 mW
1.75	0.10	1.65	0.38	1.37
2.65	0.35	2.30	0.85	1.80
3.45	0.65	2.80	1.35	2.10
3.85	0.85	3.00	1.60	2.25
4.25	1.05	3.20	1.87	2.38

TABLE 3.2: Measured transmitted and absorbed pump power (P_{tr} and P_{abs}) for different incident pump powers and two seeder power levels (20 mW and 600 mW).

The amplifier output power was characterized at three different seeder wavelengths (1025 nm, 1029 nm, and 1033 nm) for a fixed pump power equal to the maximum available. Under conditions of strong pump absorption saturation, in quasi-three-level (Q3L) materials there is an interplay between the signal power and the absorbed pump. For this reason, during the design of the amplifier, it is highly beneficial to employ an appropriate numerical model to predict pump absorption as a function of gain, doping concentration and incident pump intensity.

In the laboratory, a numerical model for the simulation of this type of amplifier, in both single-pass and multi-pass configurations, was already developed [16]. I adapted this model to the spectroscopic parameters of Yb:KYW and to the specific characteristics

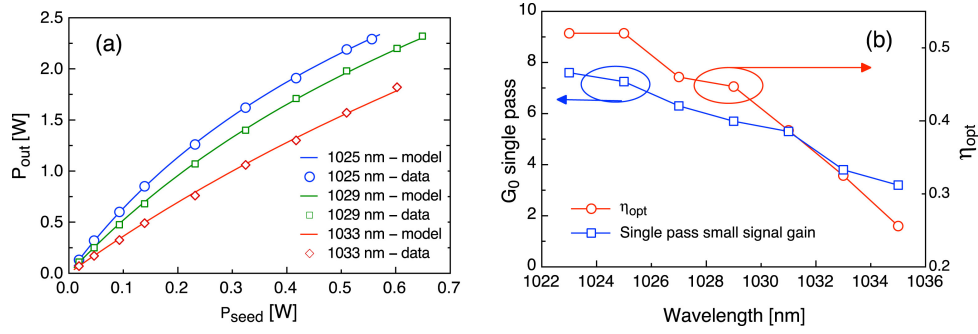


FIGURE 3.7: Single-pass amplification experiments results. (a) Output power as a function of the incident seeder power at maximum pump power (incident $P_{pump} = 4.25$ W). Results are presented in detail for seeder wavelength of 1025, 1029 and 1033 nm. (b) Single-pass small signal gain (in blue) and optical-to-optical power extraction efficiency as a function of the seeder wavelength (in red).

of the amplifier under study. The experimental results obtained were then used to “calibrate” the parameters of the model, in particular to adapt the nominal values of the cross sections we obtained from literature [48] to the one that better fits our results. As shown in Fig.3.7, the model reproduces the experimental data very well, provided that one accepts a reduction of $\sim 20\%$ in the nominal values of the Yb:KYW cross sections. This correction is fully compatible with the intrinsic uncertainty of these data and with possible thermal effects, which may be responsible for the reduction of the nominal values measured at room temperature [48].

Compared with the same input power of 500 mW the maximum output power achieves ≈ 2.3 W at 1025 nm and drop to 2 W, 1.5 W at 1029 and 1033 nm respectively.

The measured small-signal gain varied from about 7.5 at 1023 nm to 3.2 at 1033 nm (Fig. 3.7(b) blue), closely following the shape of the Yb:KYW emission cross-section for the Nm-polarization. The optical-to-optical extraction efficiency

$$\eta_{opt} = \frac{P_{out} - P_{seed}}{P_{abs}} \quad (3.4)$$

was remarkable for a single-pass configuration, reaching up to 50% near the peak gain region and gradually decreasing to around 30% at longer wavelengths, in line with the reduced active medium emission cross section (see Fig. 3.7(b)red). These results suggest

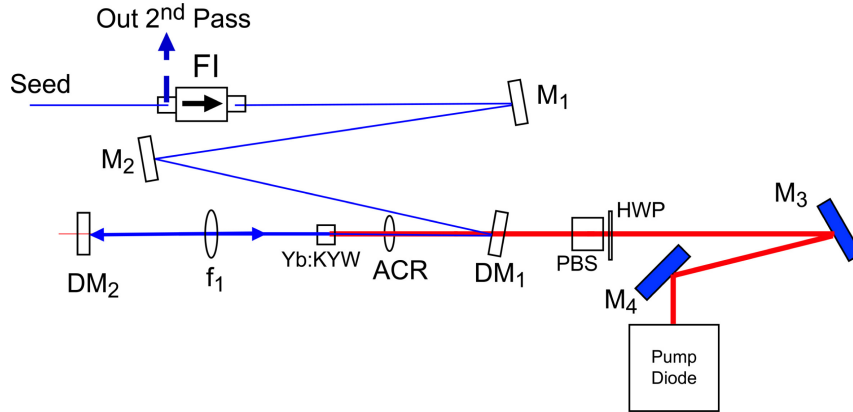


FIGURE 3.8: Double pass experiment setup: FI: Faraday Isolator 93% transmittivity; DM1, DM2: Dichroic Mirror High Transmittivity (HT) at 980 nm and HR at 1000-1100 nm; Yb:KYW: Ng-cut, 3-mm, 9.5%; ACR: Achromatic lens $f = 25$ mm, PBS: Polarized Beam Splitter; HWP: Half-Wave-Plate

that implementing a double-pass configuration would further enhance the overall small signal gain, allowing the amplifier to reach higher gain saturation in the red region of the seeding spectrum.

This has the beneficial effect of producing a more uniform spectral output, which is particularly important for amplifying ultrashort pulses with a broad bandwidth.

3.2.3 Double-Pass Amplification

A double-pass configuration was implemented starting from the Single pass setup, using a dichroic plane mirror (DM₂) and a simple 2f–2f telescope to re-image the seed beam back in the crystal. The 2nd pass output power is extracted by the Faraday isolator as shown in fig. 3.8

As expected this double-pass geometry improved gain saturation, especially at the shorter wavelengths of the seeder tuning range. Figure 3.9 (a) shows that at 1025 nm the maximum output power of 2.5 W was achieved for a seed power of ≈ 500 mW, with small-signal gain values reaching 35. The gain remains remarkably high at 1029 nm with 2.3 W maximum output power and then power drops to almost 1.8 W at 1033 nm with an increase of approximately 20% with respect to the single pass setup.

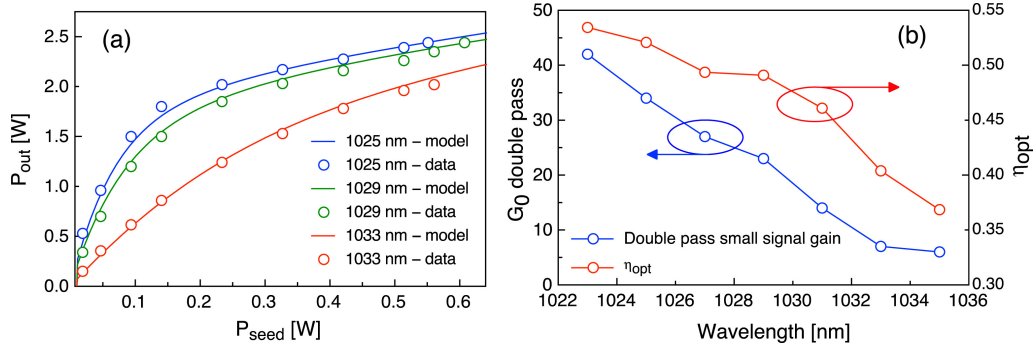


FIGURE 3.9: Double-pass amplification experiments results. (a) Output power as a function of the incident seeder power at maximum pump power (incident $P_{pump} = 4.25$ W). Results are presented in detail for seeder wavelength of 1025, 1029 and 1033 nm. (b) Double-pass small signal gain (in blue) and optical-to-optical power extraction efficiency as a function of the seeder wavelength at 500 mW input power injection (in red) .

This configuration helped to equalize extraction efficiency across the full tuning range, as it can be seen in the wavelength-dependent output power plots of Fig.3.9(a). The extraction efficiency shows a clear improvement for longer seeder wavelengths, where the emission cross-section is lower, leading to $\eta_{opt} > 35\%$ at 1035 nm. The efficiency in the region 1025-1030 nm remains remarkably high ($\geq 50\%$).

3.2.4 Femtosecond Amplification Performance

To evaluate the amplifier performance in the ultrafast regime, the seeder was configured to operate in mode-locking regime, delivering femtosecond pulses. Figure 3.10 shows the results of the double-pass amplification experiments for three representative seeder central wavelengths: 1026 nm, 1029 nm, and 1035 nm. As anticipated from the CW characterization, despite the slightly lower available average power in mode-locked operation, the higher small-signal gain on the blue side of the tuning range allows for effective amplifier saturation. This results in comparable output performance for central wavelengths of 1026 nm and 1029 nm, with maximum output powers exceeding 2 W.

A detailed example for the 1029 nm seeding central wavelength is shown in Fig. 3.11. The autocorrelation traces and corresponding optical spectra demonstrate that the seed pulse optical spectrum and duration were only marginally affected by the amplification

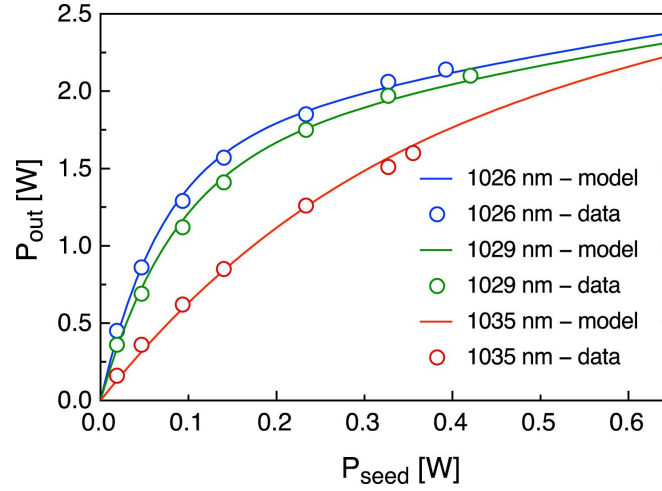


FIGURE 3.10: Double-pass amplification experiments results when seeding with femtosecond pulses at the maximum pump power (incident $P_{\text{pump}} = 4.25 \text{ W}$). Results are presented in detail for seeder central output wavelength of 1026, 1029 and 1035 nm. Dots are experimental results, solid curves are the numerical model predictions

process. The amplified pulse duration remained below 300 fs, with a time–bandwidth product (TBP) around 0.4 close to the transform limit of 0.32 expected for ideal Sech^2 -shaped soliton pulses since the residual chirp is very weak, as for the injected seeder pulse. The optical spectrum was also well preserved, exhibiting only a slight blue-shift in the peak wavelength, likely due to the asymmetry of the gain profile which favors shorter wavelengths. Both spectral and temporal characteristics of the amplified pulses were summarized for the three seed wavelengths tested in Table 3.3. To better understand the impact of amplifier saturation, these measurements were repeated for two different seed average powers (20 mW and 400 mW) at the maximum available pump power (4.25 W). This allowed us to compare performance under modest and significant saturation conditions in double-pass operation. In general, both the pulse width and spectral shape were well maintained throughout the amplification process. The only notable deviation occurred for the longest seeder wavelength (1035 nm), where the gain cross-section is lower and the spectral distribution of the gain becomes more asymmetric. In this case, a moderate spectral reshaping was observed, including a slight broadening and a blue-shift of the output peak. Nonetheless, the amplified pulses retained durations close to the seed pulses and maintained a TBP near the transform limit, confirming that the amplifier

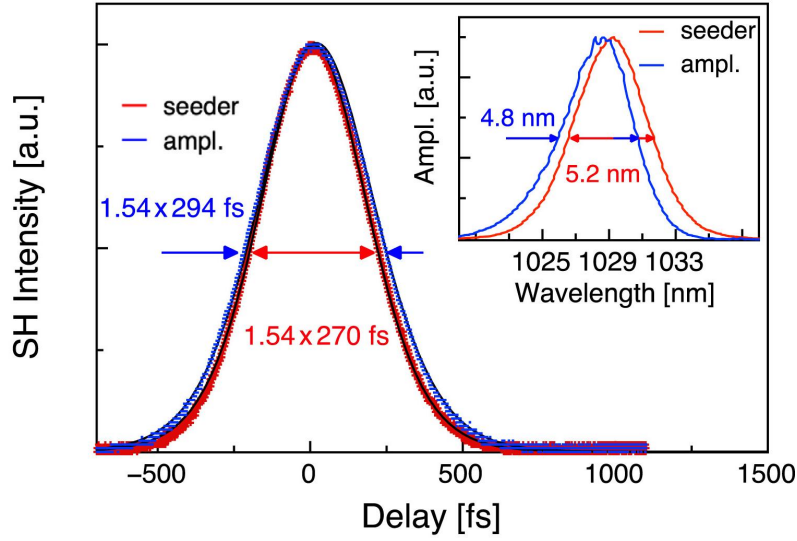


FIGURE 3.11: Autocorrelation trace of the seeder pulses at the central output wavelength of 1029 nm (red) and of the amplified pulses (blue). In the inset it is shown the corresponding optical spectrum. Incident $P_{\text{pump}} = 4.25$ W, seeder power $P_{\text{seed}} = 400$ mW

effectively supports ultrashort pulse amplification with minimal temporal and spectral distortion.

	$\lambda_c = 1026$ nm		$\lambda_c = 1029$ nm		$\lambda_c = 1035$ nm	
	τ_p [fs]	$\Delta\lambda$ [nm]	τ_p [fs]	$\Delta\lambda$ [nm]	τ_p [fs]	$\Delta\lambda$ [nm]
Seeder	280	5.8	271	5.2	235	5.9
$P_{\text{seed}} = 20$ mW	308	5.2	295	5.3	259	7.4
$P_{\text{seed}} = 400$ mW	300	5.5	294	4.8	258	6.4

TABLE 3.3: Summary of mode-locking regime results for different seeder central wavelengths λ_c and seed power levels. The amplifier operated at maximum pump power ($P_{\text{inc}} = 4.25$ W). Reported values: pulse duration τ_p , spectral FWHM $\Delta\lambda$, and output power P_{out} .

To conclude, we present the results of the beam quality measurements performed after the second pass through the amplifier, with the pump both switched off and on. The seeder spatial beam profile, which was already nearly diffraction-limited with measured beam quality factors shown in Figure 3.12 of $M_x^2 = 1.07$ and $M_y^2 = 1.03$, remained practically unchanged after amplification. This confirms the excellent mode overlap and minimal beam degradation within the active region, even under strong pump conditions (almost 4 W absorbed in the 3-mm-long Yb:KYW crystal).

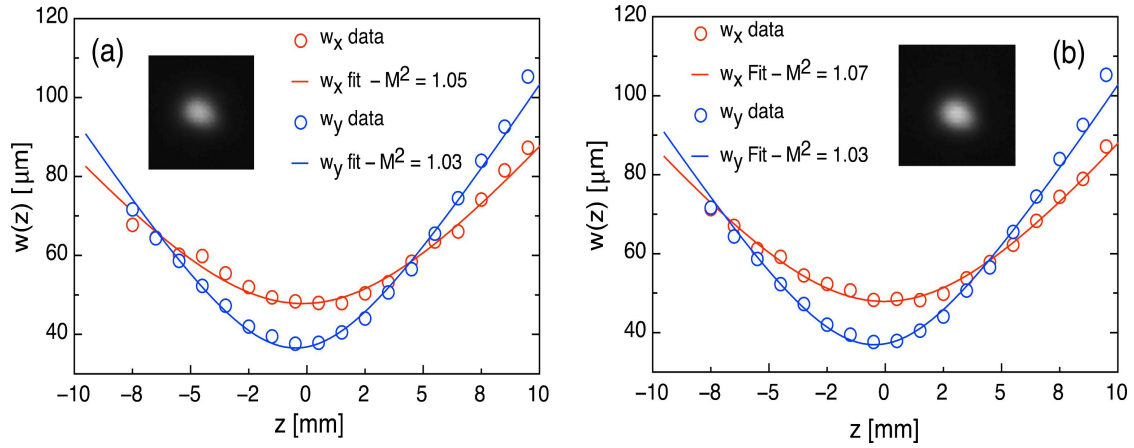


FIGURE 3.12: Beam quality measurement results in double pass setup for seeder operating at 1025 nm and 400 mW, (a) with the pump switched off and (b) at the maximum pump power (incident $P_{\text{pump}} = 4.25 \text{ W}$)

3.3 Power up-scaling strategies

In this section, I will address the problem of how to optimally exploit the second pump diode in order to achieve power scaling of the amplifier system. Different strategies can be considered, each with specific advantages and drawbacks.

The first and simplest approach was to keep the original setup unchanged. Initial measurements were carried out with the new pump module operating with a single diode, as described in Section 3.4, and then by simply switching on the second tapered diode as a “power boost.” This solution preserved the compact footprint of a single amplifier stage, but its effectiveness was limited. Since the second diode is polarized along the optical N_p axis, its absorption in the crystal was relatively weak, and the additional contribution amounted to only about 1 W at high injection levels.

In the laboratory implementation, particular care was taken to protect the pump diodes from potential back reflections, which could cause serious damage. A polarization-independent Faraday isolator was therefore introduced. However, this prevented the two pump beams from being perfectly overlapped after passing through the isolator, since it determines a lateral shift at the output for the two orthogonally polarized beams. To solve this problem, we used a pair of polarizing beam splitters to separate the path of the two beams and recombine them, but this significantly complicated the overlap inside the

active medium and introduced additional losses that reduced the available pump power. To overcome this limitations we also considered a different strategy consisting in the use of two separate amplification stages, each pumped by a single tapered diode and each employing a different Yb:KYW crystal with optimized length and doping concentration. This configuration enabled higher pump absorption at each stage and offered the additional advantage of tailoring the seed and pump mode dimensions independently for the two stages. Nevertheless, the overall improvement remained modest. In particular, for low input seed powers in the 10–100 mW range, which was the regime of greatest interest for the application we had in mind (a compact, high gain pre-amplifier in a multi-stage femtosecond high power amplification chain), no substantial benefit was observed. For this reason, the most attractive solution proved to be the single-stage amplifier with two crossed crystals arranged in a multi-pass geometry.

The four-pass configuration provided a high level of saturation, which in turn resulted in a reasonably flat gain spectrum. This characteristic is especially valuable for achieving homogeneous amplification across all spectral components of the seed pulses. The main problem of this setup, however, was the overlap between the pump and the seeder along the relatively long (6 millimeters in total) two-crossed crystal active medium. This resulted in a sub-optimal optical-to-optical extraction efficiency. Even so, the four-pass amplifier proved capable of delivering very high gain in the desired low-injection regime.

During my trainee-ship at Pantec Biosolutions, the crossed-crystal configuration was revisited under improved experimental conditions. In this case, the seed source was a fiber laser with a broader spectrum of about 15 nm centered at 1035 nm, which was well matched to the gain medium. A significant performance improvement was observed when operating without the Faraday isolator, as this allowed better overlap of the pump beams inside the crystals. Furthermore, the active media cooling system was more efficient, which contributed to enhanced thermal management and overall performance.

3.4 Experiments with the new pump module - Single-crystal amplifier

As discussed in section 3.2, interesting and promising results were obtained using a single Yb:KYW crystal and a single tapered-diode for pumping. At the beginning of my PhD, I had the opportunity to exploit a new pump module based on two-polarization-coupled tapered diodes described in Chapter 1. The first step in this investigation was to test a simple optical amplifier configuration, similar to the one shown in Figure 3.8, using this new power up-scaled module. The new pump module did not feature exactly the same output beam characteristics; therefore, in order to obtain the desired waist of $25\ \mu\text{m}$ in the 3-mm long Yb:KYW crystal (which was unchanged from previous experiments), we employed a $f = 40\ \text{mm}$ achromatic lens.

The seeder wavelength was set at $1030\ \text{nm}$ in CW regime and the polarization was oriented along the Nm-axis of the crystal. At first we switched on only one diode (the more powerful of the two) and we verified whether comparable performance to previous results (see Sec. 3.2) could be reproduced with a single diode. After completing the measurements with one diode, the second diode would be activated to provide a final power boost, allowing us to characterize the enhanced performance.

The incident pump power of the single diode was $4.7\ \text{W}$. Initially, we measured the output power after the first pass through the crystal. The results are shown in Figure 3.13. At the maximum incident seeder power of $\sim 475\ \text{mW}$, we obtained a maximum output power of $1.8\ \text{W}$ (Figure 3.13(a)). The corresponding gain was approximately 3.8 (Fig. 3.13(b)). Under these conditions, the absorbed pump power was approximately $3.5\ \text{W}$, yielding an optical-to-optical efficiency of almost 40% (Eq. 3.4).

The numerical model shows excellent agreement with the experimental data (dots in the figure 3.13(b)). According to this model, the small-signal gain was $G_0 = 5$. To perform the simulations, we used the same emission and absorption cross sections for Yb:KYW as in the preliminary analysis (with the same $\sim 20\%$ reduction factor used in the previous case). The only adjustment in the simulation parameters regarded the pump and seed

beam waists: we used a pump waist of $26\text{ }\mu\text{m}$ and a seed waist of $24\text{ }\mu\text{m}$, reasonably similar to the expected ones.

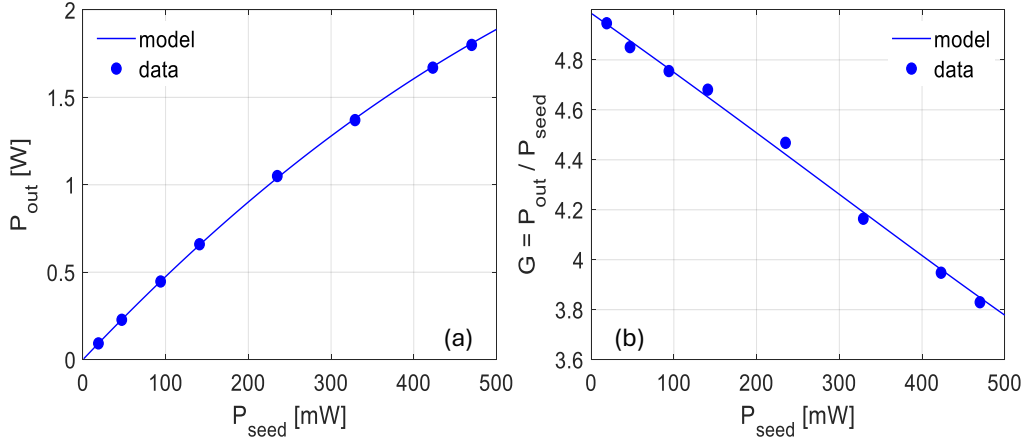


FIGURE 3.13: Single-pass amplifier results using a single Yb:KYW crystal. (a) Output power as a function of seed power. (b) Gain as a function of seed power. Absorbed pump power: 3.5 W, seed wavelength: 1030 nm. Dots represent experimental data; solid lines show the model predictions.

Following the same procedure, we also tested the double-pass configuration while maintaining the Nm-axis polarization. In this setup, the beam was re-imaged into the crystal for a second pass, and the amplified output power was measured after the Faraday isolator. The results are presented in Figure 3.14.

In this configuration, the amplifier clearly shows saturation of the gain for incident seed power exceeding $\sim 200\text{ mW}$, as shown in Figure 3.14(a). At a maximum seed power of 570 mW, the amplifier delivered an output power of 3.1 W, corresponding to a gain of approximately 5.5. The small-signal gain retrieved from the experiments is $G_0 \approx 18$.

Compared to the single-pass configuration, this setup demonstrated significantly improved performance. Nearly the entire incident pump power of 4.7 W was absorbed, with only 0.2 W of residual transmitted pump power. As a result, the optical-to-optical efficiency exceeded 55%, as calculated using Equation 3.4, which is a remarkable result for a two-passes amplifier.

To reproduce the experimental results with our numerical simulations, it was sufficient to make a minor adjustment to the pump and seed beam sizes in the model (on the

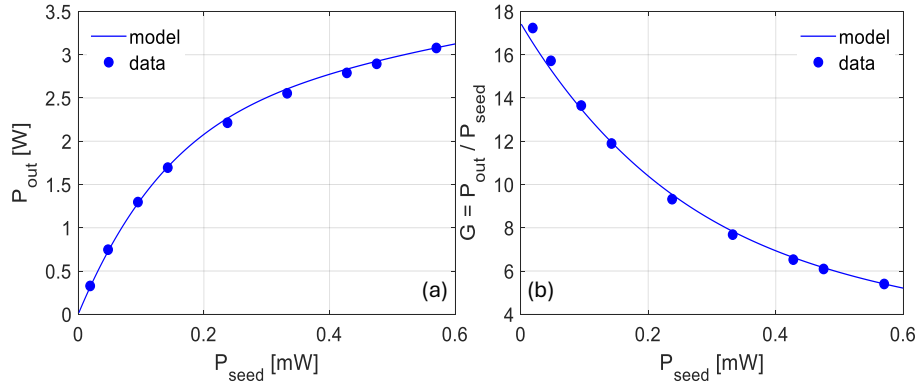


FIGURE 3.14: Double-pass amplifier results. (a) Output power as a function of seed power. (b) Gain as a function of seed power. Absorbed pump power: 4.5 W, seed wavelength: 1030 nm. Dots represent experimental data; solid lines represent the model predictions, which account for optical losses including those from the Faraday isolator.

order of a few μm). After completing the measurements with only one tapered-diode, we proceeded to test the amplifier in a double-pass configuration by turning on the second, less powerful tapered diode. This resulted in a total incident pump power of 8.5 W, given the 3.8 W provided by the second diode. As anticipated in Sec. 3.3, the Faraday isolator spatially separates the two pump beams. To accommodate the second diode, a dedicated optical path was implemented: two PBS cubes and two dielectric mirrors were employed to recombine the two beams. However, LD1 already delivered approximately 500 mW less output than LD2, and the additional optics introduced further transmission losses of about 10%.

Figure 3.15 shows a direct comparison of the amplifier performance in terms of both output power and gain for the single-diode (blue curves) and the double-diode pumping (red curves). Regarding the small-signal gain, a modest improvement was observed (the small signal gain increased from $G_0 \approx 18$ to $G_0 \approx 20$). This marginal increase can be attributed to two main reasons:

- the second diode is polarized along the Np-axis, which has a lower cross section (see Fig. 2.6), therefore the absorption of the additional pump power provided by the second diode is limited;

- as discussed in Sec. 3.4 the amplifier work in a regime of saturation of pump absorption, hence at very low seeder power, (the "small signal gain" condition) pump absorption is even more difficult.

Indeed, the most significant improvement was observed in the strong injection regime, where the output power increased from 3.1 W to 3.9 W, as shown in Figure 3.15(a). The total absorbed pump power in this configuration was approximately 5.5 W, leading to an optical-to-optical efficiency (as defined in Equation 3.4) of nearly 60%. This is quite a remarkable value and it is made possible by the excellent pump beam quality offered by the tapered-diodes that allows for a very good spatial overlap between seed and pump volume inside the active medium. Nevertheless, the efficiency, if calculated with respect to the incident pump power, is now only 40%. This is mainly due to the highly inefficient absorption of the pump provided by the second tapered diode, which is clearly the main limitation of this otherwise extremely simple setup.

These results indicate that even better amplifier performance could be achieved if the pump from both diodes were aligned with the Nm -axis, where absorption and thus overall energy transfer is more effective.

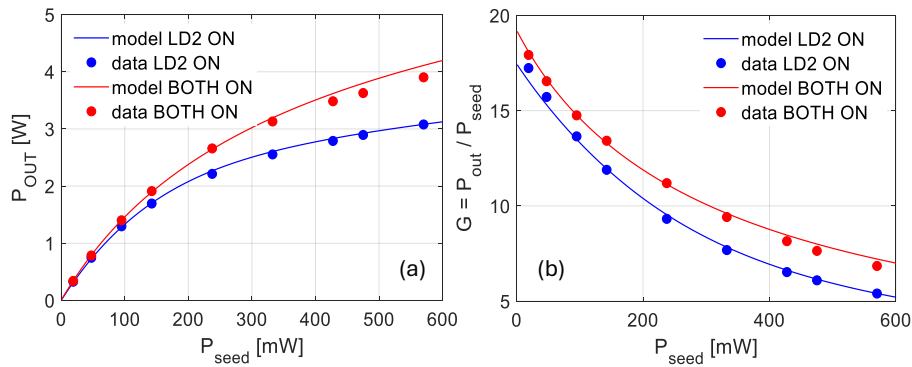


FIGURE 3.15: Double-pass amplifier results with one diode on; incident pump power: 4.7 W (in blue) and with both diodes on; incident pump power: 8.5 W (in red). (a) Output power as a function of seed power. (b) Gain as a function of seed power; seed wavelength: 1030 nm. Dots represent experimental data; solid lines represent the model predictions

3.5 Two-stages amplifier

Following the characterization of the single-crystal Yb:KYW amplifier (see Section 3.4), we realized that the limited seed power of 500 mW was insufficient to fully saturate the gain medium and thus take advantage of the total available pump power. To address this limitation, we designed a new amplifier configuration consisting of two sequential single-pass stages, each pumped by an independent diode. The first stage was pumped by the less powerful diode, while the second stage used the most powerful one.

In the first amplifier stage, we used the same Yb:KYW crystal employed previously: 3 mm-long with 9.5% doping. For the second stage, given the increased seed power available after the first amplification, we chose a longer Yb:KYW crystal (6-mm) with a lower doping concentration (5%). This strategy allowed us to relax the pump beam focusing requirements, facilitated more effective pump absorption. Furthermore, the stronger seed intensity ensured sufficient stimulated emission, enabling better exploitation of the pump power.

In both amplifier stages, the seed and pump polarizations were aligned along the N_m axis of the crystals. A schematic of the simplified setup is shown in Fig. 3.16. A polarizing beam splitter (PBS) was used to separate the two diode beams. The pump power at the first stage, after accounting for losses in the optical path, was 3.6 W, while the second stage received 4.9 W.

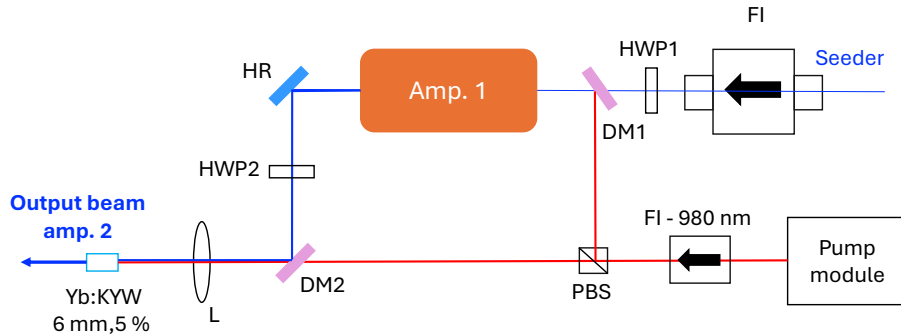


FIGURE 3.16: Schematic layout of two stages Yb:KYW amplifier. FI-980 nm: diode isolator; FI: Faraday isolator; PBS: polarizing beam splitter (980 nm); DM1, DM2: dichroic mirrors; HR: high-reflectivity mirror; HWP1, HWP2: half-wave plate; L: achromatic lens, $f=40$ mm (AC254-040-B);

To keep the setup compact and simple, both the pump and seed beams were focused onto the active medium using a single achromatic lens with 40 mm focal length. The measured pump beam waist was approximately $30\ \mu\text{m}$, while the seed beam waist was about $26\ \mu\text{m}$. The system effectively behaves as two independent amplifiers: a first stage in double-pass and a single pass final stage. The first stage, injected with limited seeder power, uses a double-pass configuration to maximize pump absorption and overall gain. The second stage, having a higher input signal level, operates in a single-pass configuration because the output of the first pass is sufficient to effectively saturate the amplifier.

The first stage amplified the 500 mW seed to 1.8 W, which was sufficient to completely absorb the pump in the second stage. Without seed injection, the absorbed pump power in the second stage dropped to 3.5 W.

The performance of the second amplification stage is shown in Fig. 3.17. By increasing the pump in the first stage, we could change the input power in the second stage from about 100 mW to 1.7 W. The maximum power at the end of the amplification chain was about 3.8 W, corresponding to a net gain in the second amplifier of about 2.3. The optical efficiency, calculated via Eq. 3.4, reached 44% in the final amplification stage.

The long-crystal amplifier configuration provides a promising approach to better utilize the available pump power by increasing the absorption length and relaxing the focusing requirements. The reduced doping helps mitigate thermal issues and allows for a more uniform gain distribution. However, these advantages are balanced by the need for a higher seed power to achieve saturation and by the increased sensitivity to pump/seed mode matching over a longer interaction length.

In summary, the amplifier operates efficiently and with good gain performance, but due to the need for strong seed injection, it is not ideal for scenarios where the seed power is limited thus deviating from our original goal.

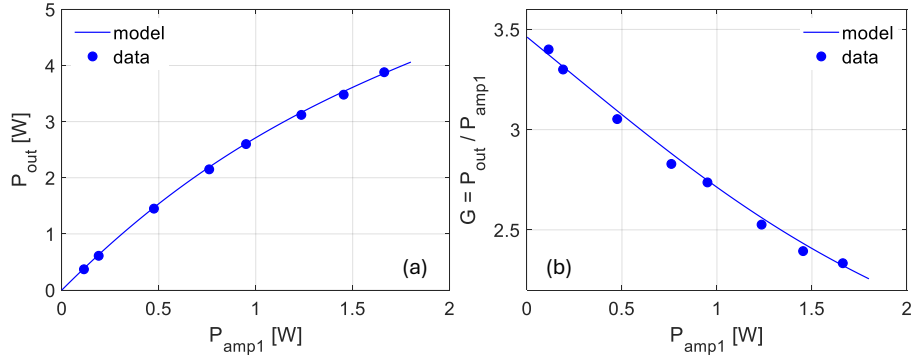


FIGURE 3.17: Single-pass amplifier results with one diode on; incident pump power: 4.9 W (a) Output power as a function of seed power. (b) Gain as a function of seed power at seed wavelength 1030 nm. Dots represent experimental data; solid lines represent the model predictions

3.6 Yb:KYW crossed crystals amplifier (Pavia setup)

3.6.1 Setup description

As outlined in Chapter , one of the central goals of this research was to develop a compact, highly efficient pre-amplifier that could operate reliably with very low seed powers on the order of a few tens of milliwatts and still deliver output powers in the multi-watt regime.

Achieving this level of performance required not only improvements in the pump source but also a rethinking of the amplifier geometry. In previous configurations based on a single Yb:KYW crystal and a single tapered diode, the maximum gain and output power were inherently limited by the available pump power. With the introduction of the new MiFem tapered diode module (described in Chapter 1), it became possible to scale the pump power to nearly double the previous values, while maintaining excellent spatial beam quality ($M^2 < 1.6$) and narrow spectral width (FWHM < 0.2 nm), thanks to the integrated Bragg grating stabilization.

However, simply increasing the pump power was not sufficient. Yb:KYW is a birefringent crystal, and its absorption cross section depends strongly on the polarization

(see Figure 2.6) of the pump relative to the crystallographic axes. In particular, absorption is strongest for light polarized along the Nm-axis. Therefore, using a single 10%-doped crystal even longer than 3 mm would not allow for efficient absorption of both pump beams, since the two tapered diodes are polarization-coupled with orthogonal linear polarizations. Only the component aligned with the Nm-axis would be well absorbed, while the orthogonal component would be transmitted for the largest part, as we observed in the experiments described in Section 3.4.

To overcome this intrinsic limitation, and fully exploit the increased pump power while preserving simplicity, we adopted a crossed-crystals configuration. Specifically, two identical Yb:KYW crystals, each 3 mm-long and 10%-doped, were mounted in an aluminum holder. The crystal holder was screwed on a water-cooled copper plate. The unique feature of this arrangement is that the two crystals are rotated with respect to each other such that their Nm-axes are orthogonal. This ensures that each pump beam polarized along one of the two orthogonal directions encounters a crystal optimized for its absorption. As a result, the total pump absorption is significantly improved without requiring longer crystals or higher doping levels.

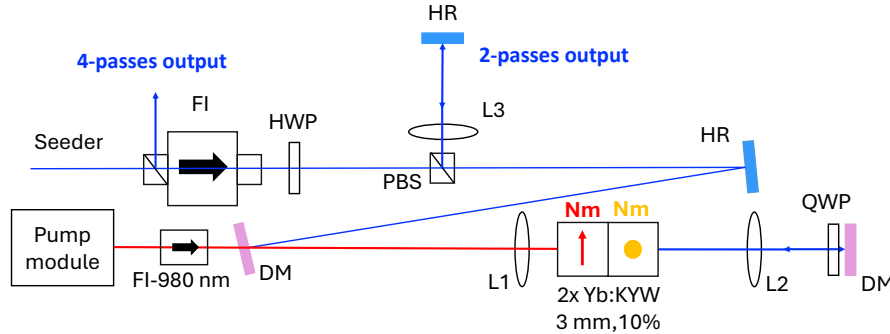


FIGURE 3.18: Schematic layout of the crossed-crystal four-pass Yb:KYW amplifier: FI-980 nm: Diode protector FI: Faraday Isolator; PBS: Polarizing Beam Splitter; DM: Dichroic Mirror; HR: High Reflectivity mirror; HWP: Half-Wave Plate; QWP: Quarter-Wave Plate; L1: achromatic lens $f = 40$ mm (AC254-040-B); L2-L3: $f = 50$ -30 mm

The optical layout of the amplifier, illustrated in Figure 3.18, is designed to permit four passes through the active medium. The pump and seed beams are spatially overlapped and focused into the crystals using a single achromatic lens (L1). This lens is

anti-reflection coated for both the pump and laser wavelengths. The optimal focal length for L1 was $f = 40$ mm, yielding a beam waist of approximately $w_p \sim 28 \mu\text{m}$ for the pump and $w_s \sim 25 \mu\text{m}$ for the seed at the focal plane inside the crystals.

The seed beam initially passed through a half-wave plate, which aligns its linear polarization along the plane of the optical table (see Fig. 3.18) parallel to the Nm-axis of the first Yb:KYW crystal. This ensures optimal gain in the first crystal, which well absorbs the power emitted by one of the two tapered diodes. When the beam passes for the first time through the second crystal, its polarization is parallel to the Np-axis, but the quarter-wave-plate, which is traveled through two-times, rotates the seed polarization so that in the second pass it is aligned to be orthogonal to the optical table, hence parallel to the Nm axis of the second Yb:KYW crystal (shown in yellow in Fig. 3.18). This rotation is critical for enabling efficient amplification in the second pass, where the beam is re-imaged back into the active region.

Upon completion of the second pass, the seed beam, which is now polarized perpendicular to the optical table, travels back toward the Faraday isolator (FI), however, before re-entering the FI, the beam is redirected by a polarizing beam splitter (PBS), which reflects vertically polarized light upward into a secondary optical arm. This segment of the amplifier includes a mirror and a lens (HR and L3 in Fig. 3.18) designed to re-image the seed beam onto the active region once more, providing the third and fourth amplification passes through the crossed crystals. After completing the final pass, the beam exits the system through the FI, which ensures unidirectional operation and protects the seed laser from any optical feedback. We observed that, due to the quite high four-passes small signal gain of the amplifier, a proper optimization of the extinction ratio of the Faraday Isolator was important to avoid self lasing of the amplifier.

The four-pass geometry allows to exploit both Nm and Np emission cross sections of both crystals during amplification. This results in the additional benefit of a partial broadening of the amplifier spectral gain bandwidth thanks to the slightly shifted peak gain for the two axis. This effect arises from the different emission cross sections and gain spectra associated with the two crystallographic directions, and their combination

leads to a broader effective gain bandwidth [49].

3.6.2 Double-pass CW regime characterization

First of all, we optimized the alignment of the amplifier in double-pass, basically placing the power meter in front of HR mirror, after the PBS, of Fig. 3.18. In this configuration, we characterized the output power of the amplifier at different seed wavelengths and input powers, while keeping the pump power to the maximum level, corresponding to an absorbed pump power of about 8.7 W. The results are shown in Figure 3.19. As expected from previous experiments and in fairly good agreement with the spectral shape of Yb:KYW emission cross sections (see Figure 2.6), the best performance was obtained at 1027 nm, reaching a maximum output power of 3.1 W with an injected seed power of 475 mW. At 1025 nm, the amplifier exhibits similar behavior under medium-to-high input seeder power, although the maximum output power is slightly lower, reaching 2.9 W. Conversely, at longer wavelengths such as 1030 and 1033 nm, the emission cross section decreases, resulting in reduced output power across all seeding levels, with maximum values of 2.7 W and 2.6 W, respectively. In this double-pass configuration, the highest optical-to-optical efficiency achieved was approximately 30%. These results indicate that the amplifier requires either a higher seed power or additional passes, as discussed in Section 3.6.3, to reach saturation possibly at all the different seeding wavelengths.

During the experiments we noticed that the amplifier went systematically through a thermal stabilization. When the pump was switched-on, initially the performance of the amplifier were better, and then the gain decreased on a time scale typical of slow thermal effects (tens of seconds). This behavior is clearly visible in Fig. 3.20, where we show the double-pass amplifier gain as a function of the seeder input power at the different tested seeder wavelength both at the "thermal steady state" (on the left) and "at the switch-on" of the pump. If, for instance, we compare the gain measured for the lower input seeder power of 20 mW, we can see that it reaches approximately 22 at 1025 nm, and drops to 16–17 at 1027 and 1030 nm, and further down to 12 at 1033 nm. In the same conditions, at the switch-on of the pump, when the amplifier crystals are basically at room temperature,

the gain measured for the different seeder wavelength is roughly 1.5 times higher. This drop in the performance of the amplifier, is less significant when the input seeder power is around few hundreds mW, likely due to the effect of gain saturation that tends to mitigate the problem. We attribute this unwanted behavior to a poor thermal contact of both the crystals with the aluminum holder and the holder itself with the water-cooled copper plate. Indeed, after the thermal steady state was reached, we could notice that the temperature of the top of the aluminum crystal holder was well above the water temperature, indicating that the crystals were poorly cooled. Unfortunately, we could not solve this issue, that clearly limited the attainable gain from our amplifier. Later, when I built the multi-pass amplifier at Pantec Biosolutions during a visiting period (see Section 3.7), I had the opportunity to work with an improved crystal holder that permitted better performance.

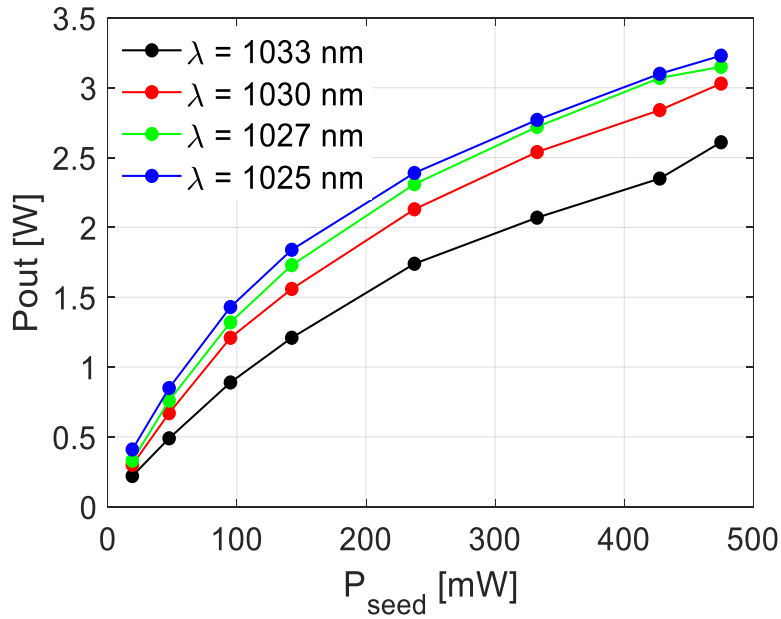


FIGURE 3.19: Double-pass amplification results. Output power as a function of the incident seed power at maximum pump power in the thermal regime ($P_{\text{pump}} = 8.7$ W). Results are shown for seed wavelengths of 1025, 1027, 1030, and 1033 nm.

The thermal drop of the gain can be explained by the temperature dependence of the emission cross section, that decreases with increasing temperature [34]. This, in turn, causes a reduction in the effective emission cross section (see Eq:2.2). The local gain

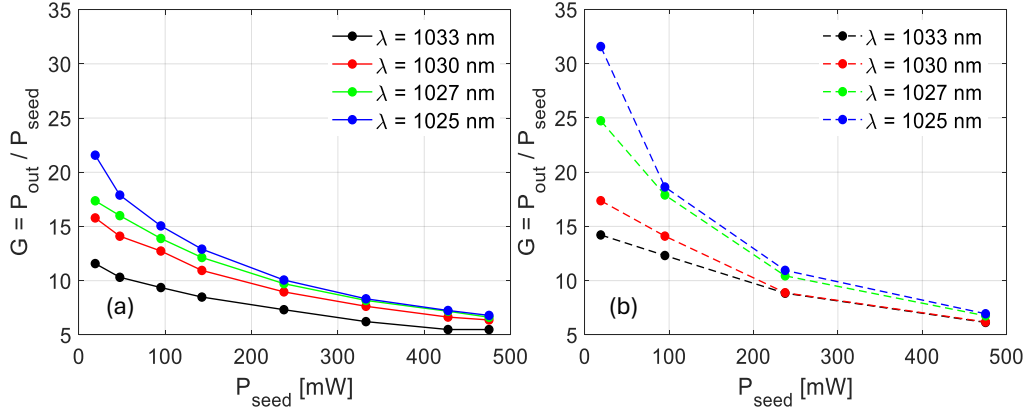


FIGURE 3.20: (a) Double-passes amplification gain as a function of the incident seeder power at maximum pump power at the thermal regime condition ($P_{pump} = 8.7$ W) at thermal regime condition (a). Same results at the start-up of the pump which represent the cold regime condition (b). Results are presented in detail for seeder central wavelengths of 1025, 1027, 1030 and 1033 nm.

coefficient of the amplifier is then given by:

$$g = \frac{\sigma_{eff} N_{tot}}{1 + \frac{P_{in}}{P_L}}, \quad (3.5)$$

where P_L is the active medium saturation power¹:

$$P_L = I_L \cdot \pi w_s^2 = \frac{hc}{\lambda_s (\sigma_e(\lambda_s) + \sigma_a(\lambda_s)) \tau_f} \cdot \pi w_s^2 \quad (3.6)$$

where h is the Planck constant, c is the speed of light in vacuum, τ_f is the fluorescence lifetime of the active medium, σ_e and σ_a are the emission and absorption cross sections at the seeder wavelength λ_s and w_s is the seed beam waist in the active medium.

The total gain can be expressed as:

$$G = \exp \left(\frac{\sigma_{eff} N_{tot}}{1 + \frac{P_{in}}{P_L}} \right). \quad (3.7)$$

¹Using the spectroscopic data of Yb:KYW and the seed beam waist w_s of our experiments, our expected saturation power is around $P_L \sim 0.5$ W.

In the small-signal limit, as $P_{in} \rightarrow 0$, or simply when $P_{in} \ll P_L$, the gain can be more conveniently estimated as:

$$G_0 \sim \exp(\sigma_{\text{eff}} N_{\text{tot}}), \quad (3.8)$$

which corresponds to the so-called small-signal gain of the optical amplifier.

This shows that even small variations in the effective cross section due to thermal effects can lead to significant changes in the small-signal gain, given the exponential dependence. Instead, the amplifier tends to be less sensitive in the saturated regime.

3.6.3 Four-passes CW regime characterization

In order to increase output power even for seeder input power < 100 mW and to better saturate the amplifier at all the different seeder wavelengths, we switched to the four-pass scheme. The results are presented in Fig. 3.21. At the minimum injected seeder power of 20 mW, we obtained a gain of about 100 at 1025 nm that dropped to about 60 at 1033 nm (see Fig. 3.22). As before, when tested in the "cold" regime, the amplifier was better performing, with a maximum gain close to 120. The four passes significantly enhanced the performance of the amplifier in the low-power seeding regime. Indeed, even at 20 mW seeding, the output power reached ~ 2 W at 1025 nm, corresponding to an optical-to-optical conversion efficiency (eq. 3.4 of approximately 23%. In the same seeding conditions, the double pass amplifier extracted a maximum power of ~ 450 mW, corresponding to an optical-to-optical conversion efficiency of only 5%. At higher seed power, the benefit of the four passes in terms of maximum output power was marginal (maximum power of 3.2 W), likely due to a worsened spatial overlap between the pump and the laser beam in the amplifier, but the main advantage was "flattening" of the optical-to-optical conversion efficiency with respect to the seeder wavelength. As it is shown in the inset of Fig. 3.21, at the maximum available seeder power, the efficiency of the amplifier is almost independent on the seeder wavelength and close to, or even slightly higher than 30%.

This behavior is also evident in the gain versus input seed power, shown in Figure

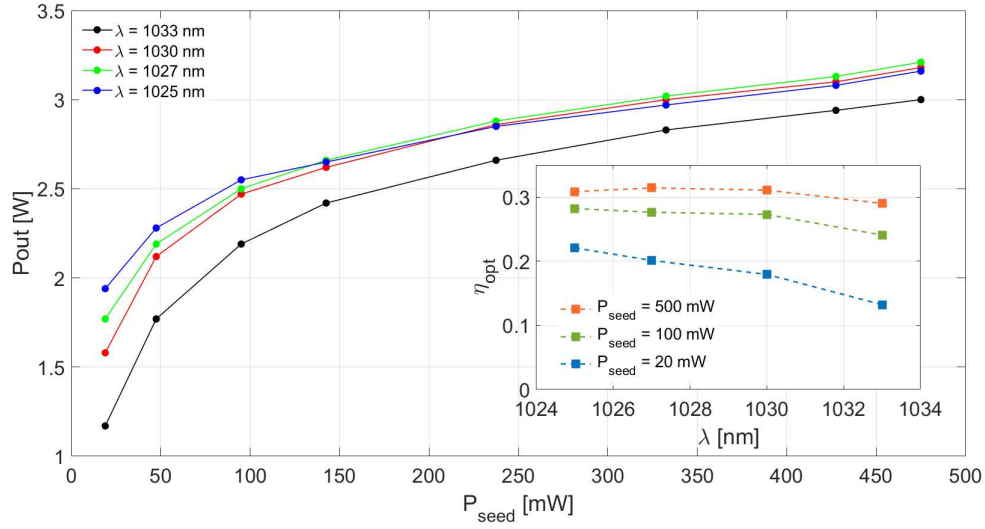


FIGURE 3.21: Four-pass amplification results. Output power as a function of the incident seed power at maximum pump power in the thermal regime ($P_{\text{pump}} = 8.7 \text{ W}$). Results are shown for seed wavelengths of 1025, 1027, 1030, and 1033 nm. In the inset, the optical-to-optical extraction efficiency is plotted versus the seed central wavelength. The three data series correspond to “low”, “medium”, and “high” injection regimes.

3.22. The maximum gain, measured at 1025 nm with a seed power of 20 mW, was approximately 100 remarkably high for a four-pass amplifier. As the seed power increased, the gain gradually decreased due to saturation, reaching a value of about 6 at 500 mW, as shown in Figure 3.22(a).

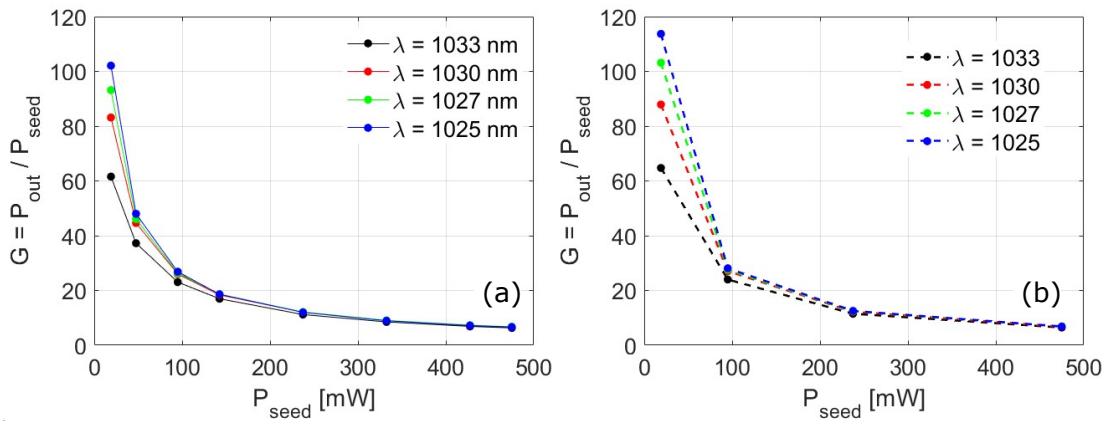


FIGURE 3.22: Four-pass amplification gain as a function of the incident seed power at maximum pump power ($P_{\text{pump}} = 8.7 \text{ W}$). (a) Gain measured at thermal steady-state. (b) Same measurement performed during the start-up phase, representing the cold condition. Results are shown for seed wavelengths of 1025, 1027, 1030, and 1033 nm.

3.6.4 Small signal gain and ASE estimation

From the experimental measurements in cw regime we performed, it is possible to determine the so-called small signal gain G_0 of the four passes amplifier, defined as the gain in the limit of vanishing seed power. This can be done by fitting the experimental data using the following expression[50]:

$$\frac{P_{in}}{P_L} = \frac{\ln\left(\frac{G_0}{G}\right)}{G - 1} \quad (3.9)$$

where G is the actual gain we measured at the given seeder input power P_{in} and P_L defined in eq. 3.6.

The result of the fit is shown in Figure 3.23 where we obtain a small signal gain $G_0 \approx 400$. The fit provides a fair estimation of the relevant amplifier parameter, i.e., the saturation power and small signal gain. It is clear that Eq. 3.9 reproduces the experimental points better in the high-injection regime. In contrast, in the low-injection regime, where even small variations in the measured input power correspond to significant changes in the gain, the model seem to underestimate the actual gain. However, it is worth noticing that to set the input seeder power injected in the amplifier, we used a combination of a HWP and a PBS. We could control the input power in the range from 20 to 500 mW, with an accuracy of about 2 mW, which may affect more significantly the low-injection measurements, where the higher value of G makes the output more sensitive to input power measurement errors.

Such a high small signal gain inherently increases the risk of a significant contribution of amplified spontaneous emission (ASE) to the total measured output power. For this reason, we decided to estimate the ASE, following the model presented by [50]. The ASE contribution can be estimated using the following relation:

$$\frac{P_{ASE}}{P_L} = \frac{\Omega}{4} \cdot \frac{G_0}{\sqrt{\ln(G_0)}} \quad (3.10)$$

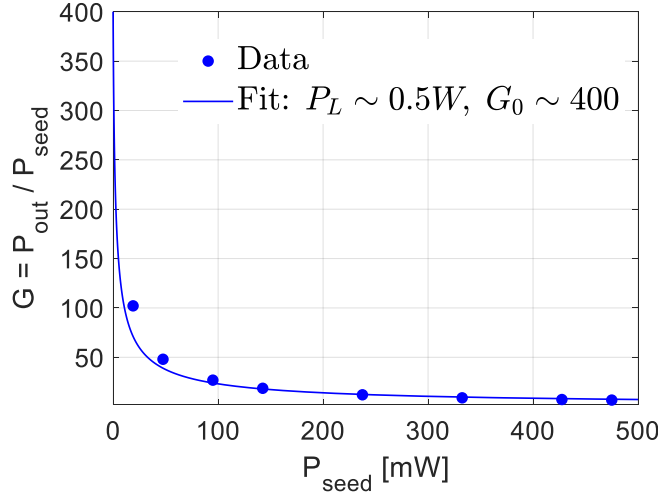


FIGURE 3.23: Four-pass amplifier gain for a seed wavelength of 1025 nm. Dots represent experimental data, and the blue line shows the fit using Equation 3.9.

where Ω is the effective solid angle under which a single spontaneously emitted photon "sees" the gain channel in the four-pass configuration and P_{ASE} is the ASE power.

If we make use of the available spectroscopic data for Yb:KYW at 1025 nm ($\tau_f \sim 300 \mu\text{s}$, $\sigma_e \approx 2 \times 10^{-20} \text{ cm}^2$, $\sigma_a \approx 0.5 \times 10^{-20} \text{ cm}^2$, and a seed beam waist $w_s \approx 25 \mu\text{m}$) in eq. 3.6 the saturation intensity is found to be approximately 25 kW cm^{-2} , and the saturation power P_L is about 0.5 W .

The effective solid angle Ω for a multi-pass system with N passes and crystal length L_c can be approximated as [50]:

$$\Omega = \frac{\pi w_p^2}{(NL_c)^2} \quad (3.11)$$

Combining Equations 3.10 and 3.11, the ASE power becomes:

$$P_{\text{ASE}} = \frac{\pi w_p^2}{4(NL_c)^2} \cdot \frac{G_0}{\sqrt{\ln(G_0)}} \cdot P_L \quad (3.12)$$

Using our experimental parameters, the calculated ASE power is less than $100 \mu\text{W}$, which agrees well with our experimental observations. This value is negligible compared to the total output power, confirming that the amplifier operates well below the ASE-limited regime.

Overall, the amplifier demonstrates excellent performance even under low seed power conditions. It delivers high gain, good extraction efficiency, and minimal ASE contribution making it a robust and efficient component for multi stage amplification systems.

3.6.5 Ultrafast regime

To fully characterize the capabilities of the amplifier in conditions relevant for ultrafast applications, we tested its performance in the pulsed regime by configuring the oscillator to operate in mode locking, generating femtosecond pulses. For this experiment, the seed laser was adjusted to emit pulses centered at $\lambda_c \sim 1027$ nm with a spectral bandwidth of approximately $\Delta\lambda \sim 6.4$ nm (FWHM), corresponding to 330 fs pulse durations with a repetition rate of 100 MHz measured at the input of the amplifier. As reported in Figure 3.24, the amplifier exhibited remarkably stable behavior, consistent with the results obtained in continuous-wave (CW) operation. The gain approached a value of about 100 for the lowest input power condition (almost 20 mW), reaching 1.9 W demonstrating also a slightly improved performances respect to the CW regime, maybe due to a better alignment, confirming the high sensitivity of the amplifier to weak ultrashort pulses.

With a maximum average seeder power of 350 mW, we obtained up to 3.1 W of average output power at the amplifier output, corresponding to a gain of nearly $G \sim 9$ in the saturated regime. This confirms that the amplifier is capable of delivering robust energy scaling even for moderate input pulse energy, typically encountered in pulse-picked or burst-mode operations.

Figure 3.25 presents the measured optical spectra and the corresponding autocorrelation traces of the amplified pulses for three representative seeder power levels: low, medium, and high, which correspond to net gain of approximately 100, 25, and 9, respectively. Across the entire operating range, the output pulses maintained a duration below 360 fs, indicating that temporal broadening during amplification was minimal (practically negligible).

A closer look to the spectra at different seeder powers (see insets of Figure 3.25) reveals two consistent features. Firstly, there is a slight blue-shift in the central wavelength

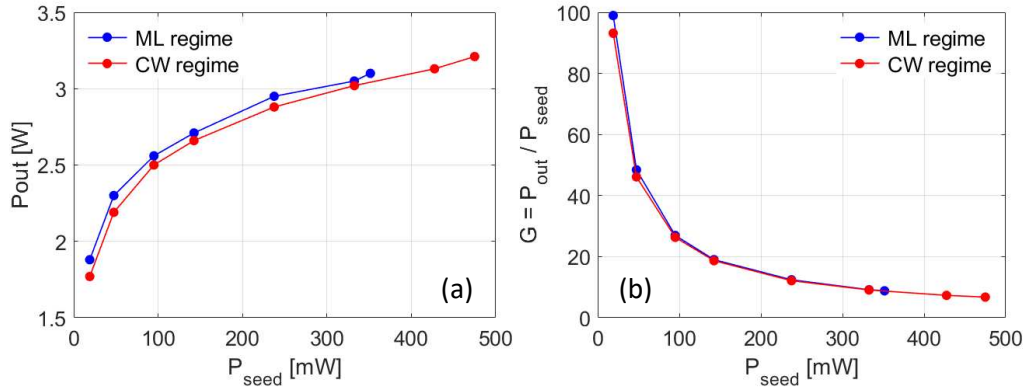


FIGURE 3.24: Four-pass amplification experiments results. (a) Output power comparison between CW (in red) and ML (in blue) regime as a function of the incident seeder power at maximum incident pump power $P_{pump} = 8.7$ W). Results are presented in detail for seeder wavelength of 1027 nm. (b) Four-pass small signal gain in CW (red) and ML (blue) regime as a function of the incident seeder power

of the amplified spectrum as the gain increases. Secondly, the spectra exhibit modest reshaping, becoming slightly narrower at high gain levels. This behavior is further accentuated at low seeder powers Fig. 3.25(a), where the gain spectrum is not flattened. In contrast, as the seed power increases (Fig.3.25(b),(c)) and the amplifier enters a more saturated regime, gain flattening naturally occurs due to the depletion of the inversion population across the gain media, which helps to preserve the original shape and central wavelength of the seed spectrum.

These results further highlight one of the key advantages of the crossed-crystal amplifier configuration: its capacity to partially mitigate gain narrowing through the simultaneous use of two orthogonal crystallographic axes. By exploiting both the N_m and N_p emission cross sections of the Yb:KYW crystals, the effective gain bandwidth of the amplifier is extended, allowing it to support broader seed spectra and preserve spectral components that would otherwise be suppressed in a conventional single-axis geometry with spectral wider pulses. This characteristic is particularly beneficial in ultrafast amplification, where maintaining spectral bandwidth is essential to preserve short pulse durations [51].

An additional and important consideration pertains to the spectral characteristics of

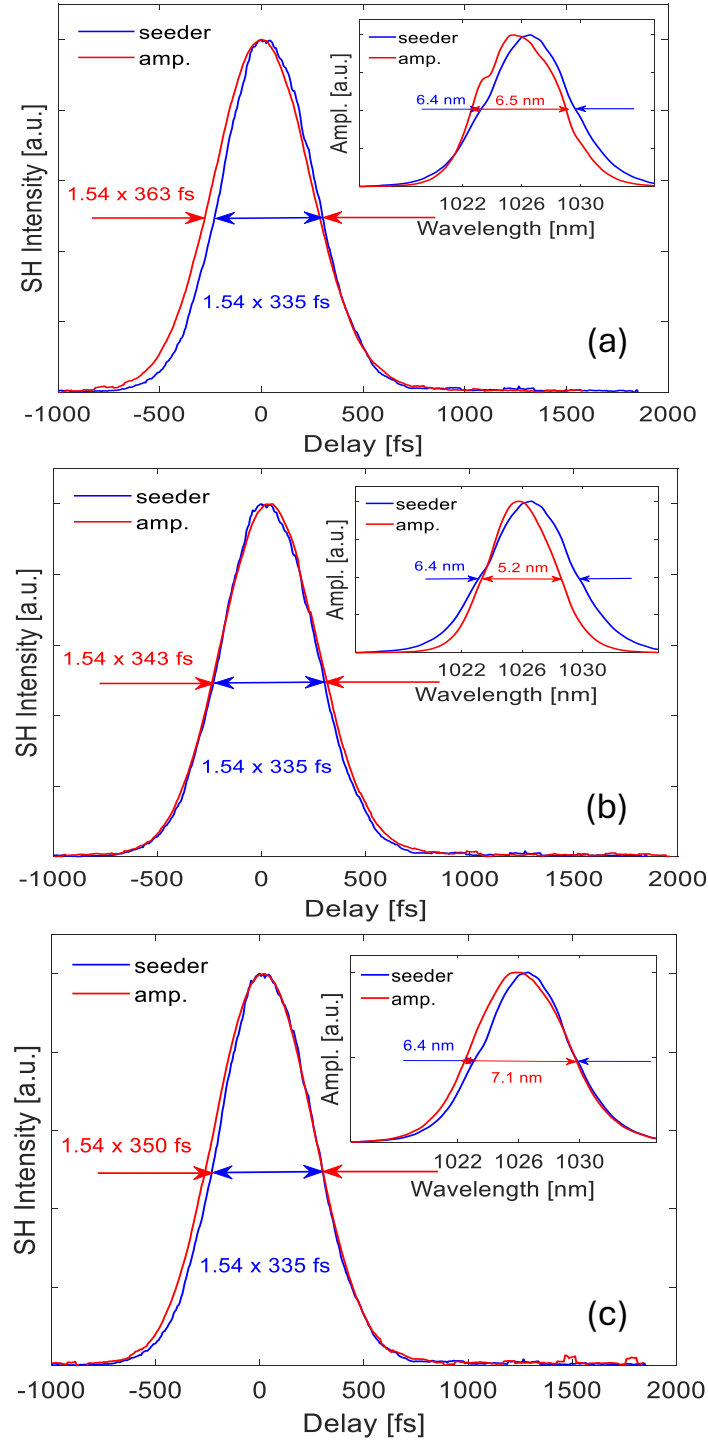


FIGURE 3.25: Autocorrelation traces and corresponding spectra of the amplified pulses at three seeder input levels: (a) $P_{\text{seed}} = 20 \text{ mW}$, (b) $P_{\text{seed}} = 100 \text{ mW}$, and (c) $P_{\text{seed}} = 350 \text{ mW}$. Insets show the amplified spectra and seeder spectrum (red and blue line respectively) for each case.

the seed pulse used in these experiments. The full-width at half-maximum (FWHM) spectral bandwidth of the input pulses was 6.4 nm, significantly narrower than the intrinsic emission bandwidth of the Yb:KYW crystal, which exceeds 20 nm for Nm,Np-axis polarizations. As a result, the extent of gain narrowing expected in this configuration is limited, as the seed bandwidth only partially overlaps the gain profile.

To quantify the expected spectral narrowing during amplification, we refer to the following relation [52]

$$\Delta\lambda_o = \frac{\Delta\lambda_i}{\sqrt{1 + \left(\frac{\Delta\lambda_i}{\Delta\lambda_g}\right)^2 \ln \sqrt{G_0}}} \quad (3.13)$$

where $\Delta\lambda_i$ is the input (seeder) spectral bandwidth, $\Delta\lambda_g$ is the FWHM of the gain spectrum of the active medium, $\Delta\lambda_o$ is the output bandwidth after amplification, and G_0 is the small-signal gain.

In our case, given that $\Delta\lambda_i/\Delta\lambda_g \approx 0.3$, the denominator in Equation 3.13 remains close to unity even for large values of G_0 , and thus has only a modest impact on the output spectral width. Substituting our experimental values into the equation yields an estimated output bandwidth of $\Delta\lambda_o \sim 5.8$ nm.

Using this result, we can also estimate the corresponding output pulse duration based on the time-bandwidth relationship. Assuming the shape of the pulse is preserved, the following expression applies:

$$\tau_o = \tau_i \frac{\Delta\lambda_i}{\Delta\lambda_o} \quad (3.14)$$

Here, τ_i and τ_o are the durations of the input and output pulses, respectively. Applying Equation 3.14 to our measured parameters yields an output pulse duration of approximately 360 fs, in excellent agreement with our measured autocorrelation traces. With 113 MHz rep. rate, this corresponds to a pulse energy of ≈ 27 nJ, yielding a peak power of:

$$P_{peak} \simeq \frac{E_p}{\tau_o} \approx 80 \text{ kW} \quad (3.15)$$

During the propagation in the four-pass amplifier, we did not observe any significant contribution of Self-Phase Modulation (SPM) or other nonlinear effects in the spectral reshaping of the pulses. The main effects are rather associated with gain narrowing and peak shifting. One common way to assess the potential impact of SPM and self-focusing in multistage amplifiers, is the evaluation of the so-called B-integral[52]. Usually values of $B \leq 1$ mean a "safe" regime, whereas significant effects start to take place if $B \sim 4$.

For the estimation of the nonlinear phase accumulation, we decided to consider only the last two passes in the amplifier, since in the first and second passes, the pulse intensity is too low to provide a relevant contribution. This corresponds to consider a propagation inside a crystal of twice the length of our sample. In order to be even more conservative (and to ease the calculation), we assumed that the intensity during third and fourth pass already corresponds to the maximum intensity we measured at the amplifier output. This produces an overestimation in the B-integral but it is still a reasonable assumption, since in the last two passes, the amplifier enters in the saturated regime and gain is relatively small.

The B-integral is defined as [52]:

$$B = \frac{2\pi}{\lambda} n_2 \int_0^L I(z) dz \approx \frac{2\pi}{\lambda} n_2 I_{out} L, \quad (3.16)$$

where $n_2 (\sim 1 \times 10^{-15} \text{ cm}^2/\text{W}$ for Yb:KYW [53]) is the non-linear refractive index, $I(z)$ is the local pulse intensity, and L is the effective propagation length. By assuming an almost constant pulse intensity in the two final amplification passes, we can substitute the integral with the product between I_{out} and L . With our experimental results in terms of output peak power ($P_{peak} \sim 80 \text{ kW}$) and amplified beam waist ($w_s \sim 25 \mu\text{m}$), we can calculate:

$$I_{out} \simeq \frac{2P_{peak}}{\pi w_s^2} \sim 8 \text{ GW/cm}^2 \quad (3.17)$$

With the above assumptions, the estimated value is approximately $B \simeq 0.6$. This confirms that nonlinear phase accumulation in our system remains limited, which is consistent with the experimental evidence.

To further investigate the amplifier behavior under more restrictive conditions, seeding with a spectrum significantly broader and more comparable to the full gain bandwidth of Yb:KYW we proceeded to test the same crossed-crystal amplifier using a femtosecond fiber laser with a 15.5 nm spectral bandwidth. The results of this second configuration, including spectral reshaping, pulse compression, and beam quality, are discussed in detail in Section 3.7.

Lastly, and of critical importance across all experimental configurations, the amplifier consistently demonstrated excellent preservation of the spatial quality of the beam. Figure 3.26 presents the beam quality measurements taken before and after amplification. With the pump off (Fig. 3.26(a)), the seed beam already exhibited a nearly diffraction-limited profile, and this quality was maintained even at full pump power (8.7 W) as shown in Fig. 3.26(b). The measured M^2 values were 1.08 and 1.09 in the horizontal and vertical axes, respectively, confirming that the spatial properties of the beam remained virtually unaffected by the amplification process. This high-quality beam propagation is attributed to the excellent brightness and low divergence of the tapered diode pumps, as well as to the careful mode matching and imaging conditions implemented in the amplifier design.

3.7 Yb:KYW crossed crystals amplifier (Pantec Biosolutions setup)

3.7.1 Setup description

At the beginning of March 2024, I had the opportunity to spend 6 months at Pantec Biosolutions in Ruggell, in Liechtenstein, and in this period I developed a second version of the crossed-crystals amplifier: The picture of the water-cooled board on which I built the setup is shown in Figure 3.27. The entire laser system developed in this configuration

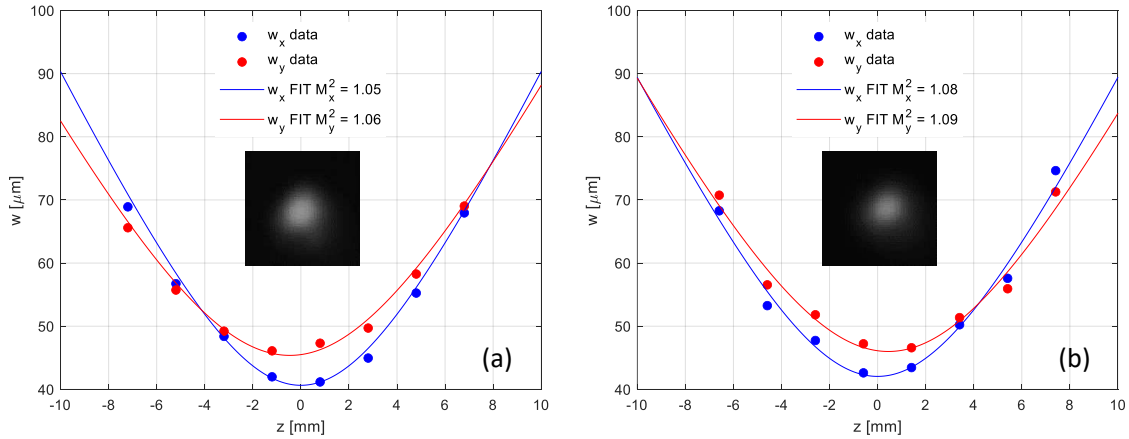


FIGURE 3.26: Beam quality measurement results in the four-pass amplifier configuration for a seeder operating at 1026 nm. (a) Measurement with the pump switched off; (b) Measurement at maximum pump power (8.7 W).

was designed with compactness and industrial applicability in mind. The total footprint of the optical board is only $60 \times 45 \text{ cm}^2$, making it well-suited for integration into industrial-board laser platforms. This compact layout not only reduces physical space requirements, but also improves thermal stability and mechanical robustness, key aspects in industrial environments.

The system employs a commercially available Yb-doped fiber laser as the master oscillator. This laser delivers positively chirped pulses with a duration of approximately 5 ps and a broad optical spectrum with a full-width at half-maximum (FWHM) of about 15.5 nm, centered around 1035 nm. This bandwidth is significantly broader than that of the in-house bulk seeder described in Section 3.1 that I used in the previously described experiments, allowing us to explore the amplifier performance in operating conditions in which the gain narrowing effects can be significant.

An acousto-optic modulator (AOM) operating in the $m = -1$ diffraction order with $> 80\%$ diffraction efficiency is placed directly after the seed source. This component enables precise control of the number of pulses injected into the amplifier chain and allows for repetition rate reduction by a factor of maximum 10. The native repetition rate of the oscillator is 40 MHz, but it can be reduced down to 4 MHz. Such pulse picking strategies are commonly adopted in industrial laser systems, to balance the energy per pulse with

thermal load and to give the laser system an additional flexibility which can be required in many applications.

After amplification, the pulses are directed to a grating-based optical pulse compressor consisting of two diffraction gratings arranged in a Treacy configuration [54]. The purpose of this stage is to temporally compress the amplified pulses and assess the minimal pulse duration achievable, taking into account spectral reshaping due to gain narrowing and the residual chirp of the input pulses. Compression results indicate that output pulses can be shortened to sub-200 fs durations, with time-bandwidth products approaching the transform limit for Gaussian pulses (more detail in 3.7.4). To verify pulse compression I used a 5 mm-long BBO crystal to generate second-harmonic (SHG) in the visible. The intensity of the SHG signal served as a guide to confirm proper temporal compression: an efficient SHG signal indicates high peak power and short pulse duration. Although not intended as a precise measurement tool, this qualitative test proved effective in the lab work and once I had at my disposal a commercial autocorrelator to actually measure the pulse duration, I verified that the optimal configuration of the pulse compressor identified with the SHG was very close to the best verified with the autocorrelator.

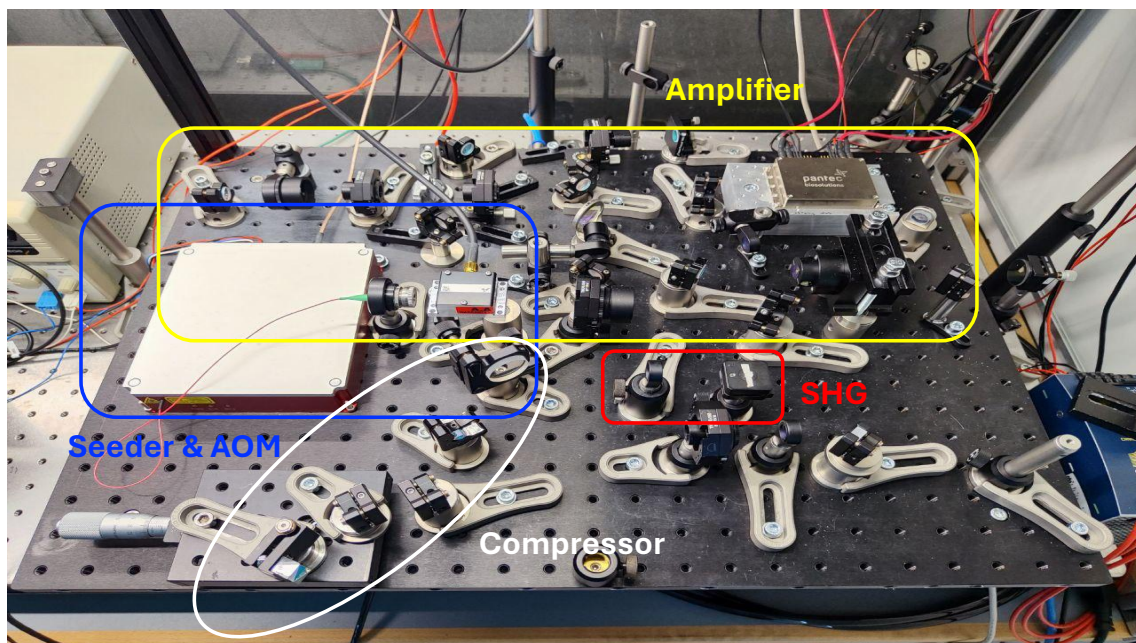


FIGURE 3.27: MOPA laser system setup put on a water-cooled board

The full Master Oscillator Power Amplifier (MOPA) configuration adopted for this experiment is illustrated in detail in Figure 3.28. The front-end source is a commercially available Yb-doped fiber laser. At the fiber output, the mode field diameter (MFD) at the fiber collimator is approximately 1 mm. To adapt this beam to the spatial requirements of the amplifier, a two-stage beam shaping system is employed. The first telescope is composed of a Regulable collimator (RFC) and lens L1, resulting in a magnification factor of $m_1 \approx 2.4$. The output collimated seed beam is then directed through a Faraday isolator (FI) to protect the seed source from potential back reflections during amplification.

Next, the beam enters a second telescope consisting of lenses L2 and L3, with a beam waist reduction factor of $m_2 \approx 1/3$. The combined effect of the two telescopes determines the beam waist at the entrance of the amplifier system. The intermediate beam waist w_0 at lens L4 is calculated as:

$$w_0 = \frac{MFD}{2} m_1 m_2 \sim 400 \mu\text{m} \quad (3.18)$$

The seed beam is then focused into the gain medium by lens L4, with focal length $f = 30$ mm, thus yielding a $w_s \simeq 25 \mu\text{m}$ in the amplifier. This is matched to the pump beam waist, $w_p \approx 25 \mu\text{m}$, ensuring optimal spatial overlap and efficient amplification.

The amplifier design is based on the four-pass crossed-crystal geometry previously described in Section 3.6.1. The same principles apply here, including the alternation of the seed beam polarization between passes to engage both crystals Nm axes. The only significant modification in this configuration is the replacement of the dichroic mirror (denoted D2 in the setup). The new dichroic mirror was specifically chosen to minimize residual reflected pump light, which could otherwise be back-reflected toward the pump module. Notably, in this setup, the pump module is not protected by a Faraday isolator, making the suppression of back-reflections especially critical for maintaining pump diode integrity and long-term system stability, but at the same time allow to further compact the total setup and more available input pump power.

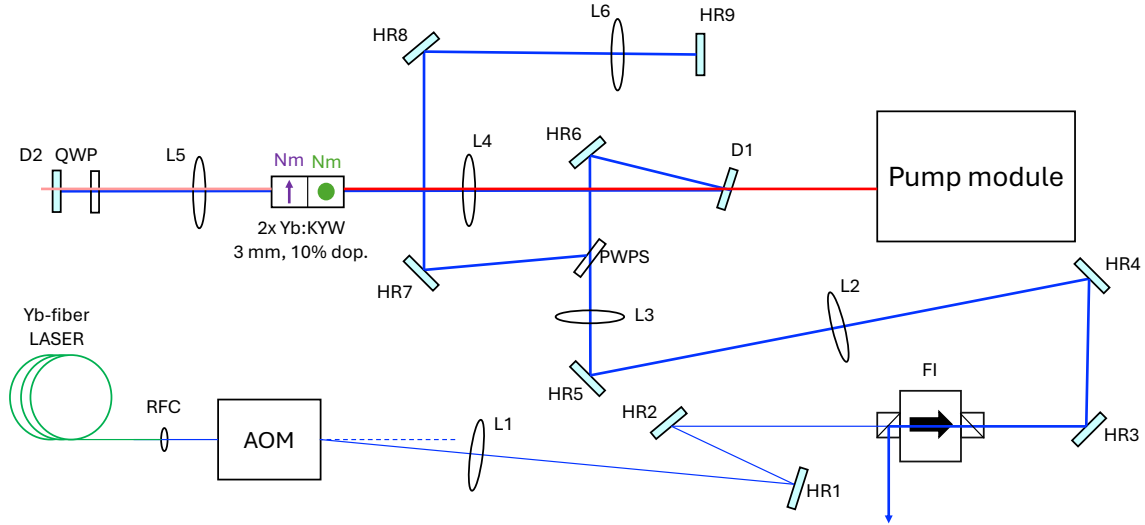


FIGURE 3.28: MOPA laser system scheme. FI: Faraday Isolator ($T = 93\%$), RFC: Regulated Fiber Collimator, AOM: Acousto-Optic Modulator, L1-L2: $f = 100$ mm, L3-L4-L6: $f = 30$ mm, L5: $f = 25$ mm, D1-D2: Dichroic mirrors (HT 980 nm – HR 1030 nm), PWPS: Polarizing-Wave Plate Splitter, QWP: Quarter-Wave Plate

3.7.2 Characterization of Gain and output power

The first step in characterizing the performance of the fiber-seeded amplifier was to measure the output power and corresponding gain as a function of the absorbed pump power. The pulses average power was about 15 mW at the input of the crossed-crystal amplifier. Given such a low input power level, the gain measurements effectively correspond to the small-signal regime, allowing for a straightforward evaluation of the amplifier intrinsic performance.

After a careful alignment of the amplifier and the optimization of the matching between the focus of the pump and the seeder in the active crystals, we obtained the results that are reported in Figure 3.29, where both the output power and gain are plotted as functions of the absorbed pump power.

As previously discussed in Chapter 1, the spatial characteristics of the tapered diodes depend strongly on the driving current. In addition, the amplifier alignment was optimized at the maximum incident pump power, in a way in which thermal lensing effects taking place in the active medium are properly compensated adjusting lenses L4, L5 and L6 (see Fig. 3.28). These aspects might explain the strange evolution of the gain/output

power as a function of the absorbed pump power we measured, which is highly nonlinear below ~ 5 W of absorbed pump power. It is worth noticing that the practical range of interest for the amplifier is around the maximum available pump power, where the system has being optimized.

At a maximum absorbed pump power of approximately 8.5 W, the system reaches an output power of 1.42 W, corresponding to a small-signal gain of $G \approx 95$ and an optical-to-optical conversion efficiency of approximately 15%. And when the maximum pump power is absorbed (10 W) the output power raise to 1.6 W With a gain $G = 110$. This represents a significant improvement compared to the previous crossed-crystal amplifier configuration tested in Pavia (see Section 3.6): under nearly identical pumping conditions (8.7 W) but with a slightly longer seed wavelength of 1033 nm—the gain reached only $G \approx 60$, and the output power was limited to 1.2 W. This means that the new setup demonstrates an enhancement of approximately 20% in both gain and output power, confirming the effectiveness of the modified geometry and the improved selection of components.

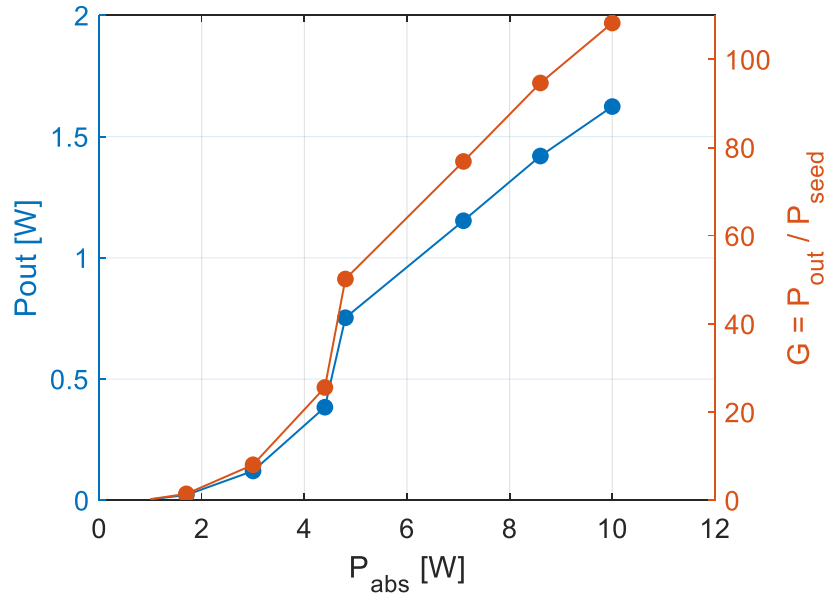


FIGURE 3.29: Measured output power (blue) and small-signal gain (orange) as a function of absorbed pump power. Seed wavelength: 1035 nm; Seed power: 15 mW.

Using the same pump power of 8.7 W, we also measured the optical gain as a function of the input seed power. The measurement was performed with a power meter whose sensitivity was on the order of mW. Under these conditions, when the full pulse train (10/10 pulses) in a period was injected into the amplifier, the measured input average power was approximately 15 ± 1 mW. To obtain the other data points, the number of injected pulses was gradually reduced using the pulse picker. The maximum decimation factor was 1/10, corresponding to an input seed average power of about 1.5 mW.

The measurement results are shown in Fig. 3.30. By fitting the results using Equation 3.9, we estimate the small-signal gain to be approximately $G_0 \approx 500$ and $P_L \approx 1.2$ W. The higher value of P_L with respect to our estimation in case of the amplification setup built in Pavia is consistent with the reduction in Yb:KYW emission cross section at longer wavelengths. Indeed, the spectrum of the fiber laser seeder (see insets of Fig. 3.34) was centered in the region 1030-1045 nm. This makes the results even more impressive, since clearly the amplifier is not seeded around the peak of the emission cross section of Yb:KYW, as it happened in the experiments carried out in Pavia.

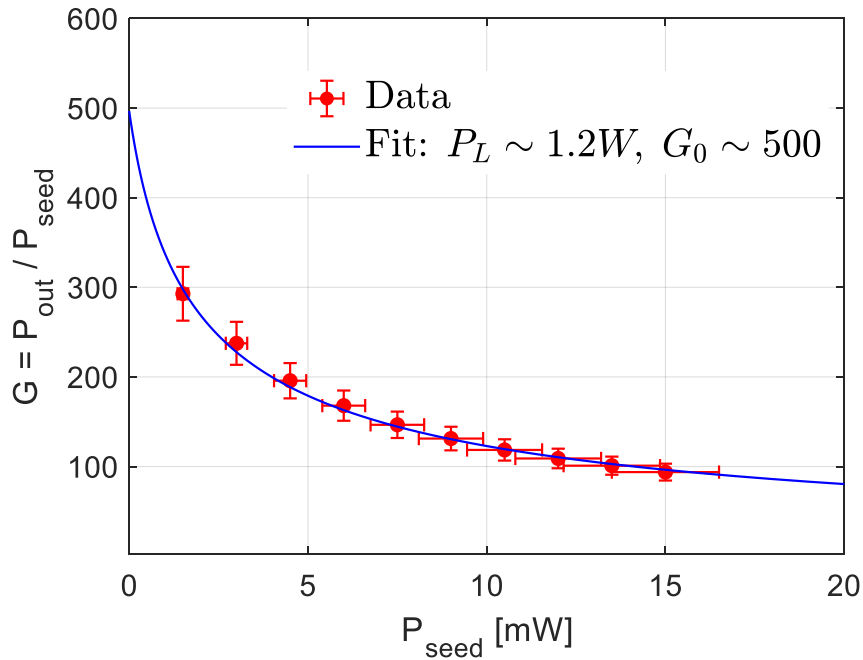


FIGURE 3.30: Measured gain as a function of input seed power. Seed wavelength: 1035 nm, 8.7 W pump power. The dots represent experimental data, while the blue line corresponds to the fit.

By using $G_0 = 500$ in Equation 3.12, we find that the total ASE power remains below 1 mW (300 μ W), confirming that amplified spontaneous emission does not affect the amplifier's performance under these conditions.

3.7.3 Compressor and SHG

As discussed in Section 3.7.1, after the amplifier stage we inserted a Tracey[55] two-pass grating compressor to shorten the amplified pulses to the minimum duration.

The amplified beam was first re-collimated using a 1:1 telescope, in order to enter the compressor with an as much as possible plane wave-front. It then impinged on a D-shaped high-reflectivity mirror (DHR) and passed through a pair of two identical diffraction gratings with 1000 groves/mm arranged in the Littrow configuration to minimize losses. A high-reflectivity prism introduced a vertical offset, allowing the retro-reflected beam to pass just above the D-shaped mirror, as it is shown in Fig. 3.31, and 3.32.

The compressor showed a remarkable efficiency of 95%, thanks to the high quality transmission gratings and a proper alignment. The prismatic retro-reflector and the second grating were mounted on a micrometric translation stage to finely tune the amount of negative Group Delay Dispersion (GDD) applied to the pulses.

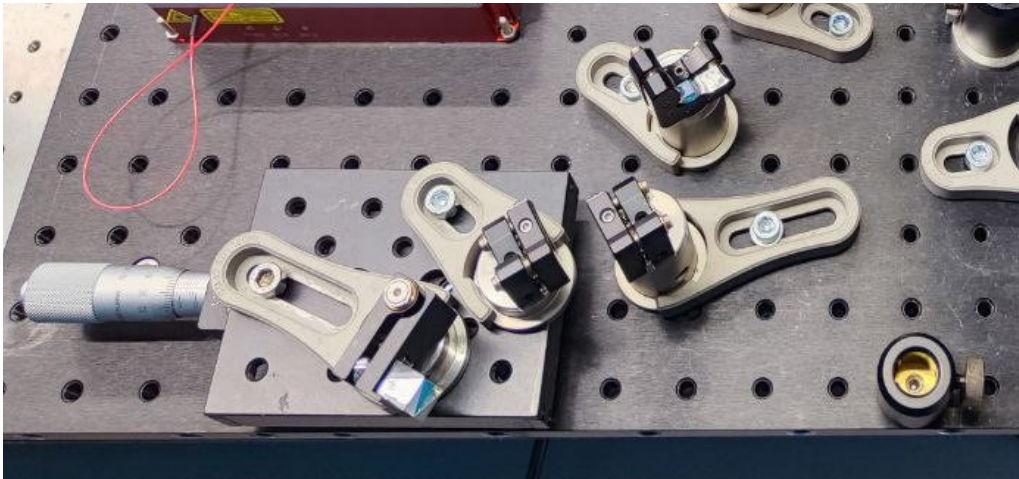


FIGURE 3.31: Photograph of the Tracey two-grating compressor.

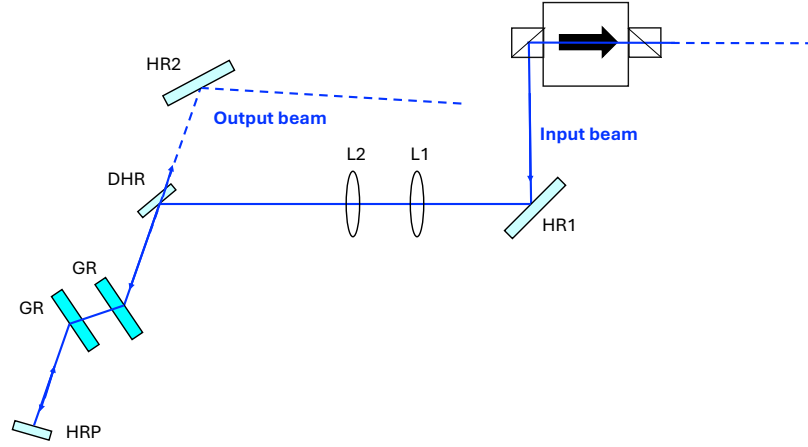


FIGURE 3.32: Scheme of the Treacy compressor. The beam at the input of the compressor is the output of the 4-pass amplifier and it is polarized perpendicular to the optical table
 . HR1-HR2: high-reflectivity mirrors at 1030 nm; L1, L2: lenses with focal length $f = 25$ mm; DHR: D-shaped HR mirror; HRP: vertical HR prism; GR: diffraction gratings (1000 lines/mm) in Littrow configuration.

During the initial phase of the optimization of the pulse duration, unfortunately I did not have at my disposal any autocorrelator. Therefore, to identify the shortest pulse duration (without the possibility to measure directly the exact value!), as already mentioned, I used a 5 mm long BBO crystal cut for Type-I phase matching at around 1030 nm, and the SHG signal was monitored via a photodiode connected to an oscilloscope, as shown in Figure 3.33.

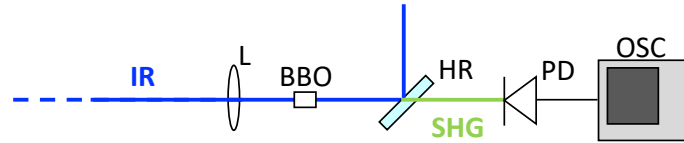


FIGURE 3.33: Schematic of the SHG stage. L: $f = 40$ mm, BBO: 5 mm-long BBO crystal, HR: IR High reflector used like a green filter, PD: fast photodiode, OSC: Oscilloscope ($R_{in} = 50 \Omega$)

The maximum SHG signal was measured when the distance between the two gratings was approximately $l = 25$ mm. The corresponding negative GDD introduced by the compressor was estimated using the grating compressor GDD equation [56]:

$$\text{GDD} = -\frac{l}{2\pi c^2} \cdot \frac{Nm^2\lambda^3}{d^2} \cdot \left[1 - \left(\frac{-m\lambda}{d} - \sin \theta_i \right)^2 \right]^{-3/2} \quad (3.19)$$

where:

- $N = 4$ is the number of grating passes,
- $m = -1$ is the diffraction order,
- $d = 1 \mu\text{m}$ is the grating period (i.e. 1000 lines/mm),
- $\lambda = 1035 \text{ nm}$ is the central wavelength ,
- $l = 25 \text{ mm}$ is the separation between the gratings,
- θ_i is the angle of incidence.

The Littrow angle θ_{Littrow} is given by:

$$\theta_{\text{Littrow}} = \arcsin \left(\frac{m\lambda}{2d} \right) \quad (3.20)$$

In our configuration, the Littrow angle was approximately 30° , and the calculated GDD was around -0.320 ps^2 .

3.7.4 Characterization of the temporal and spectral properties of the amplified beam

Just before I finished my time at Pantec Biosolutions, I eventually had at my disposal a commercial autocorrelator (APE pulseCheck) and a spectrometer to directly measure pulse duration and spectrum. To evaluate the temporal and spectral evolution of the pulses through the amplification and compression stages, we performed measurements at two distinct pump power levels: 6.5 W (intermediate pump power regime) and 10 W (maximum pump power regime). The results are shown in Figure 3.34, where each panel includes both the autocorrelation trace of the recompressed pulses and the corresponding optical spectra before and after amplification.

Already at the intermediate pump power (Fig. 3.34(a)), the spectral reshaping due to the imperfect overlap between the spectrum of the seeder and the gain bandwidth of the Yb:KYW amplifier is significant. The central wavelength has blue-shifted to about 1030 nm, and the spectrum FWHM is reduced to ~ 10 nm. The minimum compressed pulse duration in this case was about 160 fs, corresponding to a TBP of 0.43. At the full pump power (Fig. 3.34(b)), an even more significant spectral narrowing was observed, leading to a spectrum FWHM of 8.6 nm and a corresponding minimum compressed pulse duration that grows to about 200 fs, corresponding to a TBP of 0.49. This behavior is consistent with the spectral shape of the gain cross section of Yb:KYW along the Nm-axis, which is peaked at around 1020-1025 nm and progressively decreases at the longer wavelengths. This triggers a re-shaping of the pulses spectra, with the observed blue-shift and narrowing. Notably, despite the spectral narrowing, the amplifier did not introduce excessive distortion or non-linear effects, which could have hampered further compression.

The gain narrowing effect can also be estimated according to equation 3.13. If we insert our parameters $G_0 = 500$, $\Delta\lambda_i = 15.5$ nm, and $\Delta\lambda_g = 20$ nm we find that the resulting output bandwidth is approximately $\Delta\lambda_o \approx 9$ nm, which is in very good agreement with our results.

To model the temporal broadening and compression of a Gaussian optical pulse due to second-order dispersion, the pulse duration after propagation through a dispersive medium is given by [56]:

$$\tau = \tau_0 \cdot \sqrt{1 + \left(\frac{4 \ln 2 \cdot GDD}{\tau_0^2} \right)^2} \quad (3.21)$$

Where:

- τ_0 is the transform-limited pulse duration (i.e., minimum duration)
- τ is the chirped pulse duration (after dispersion)

As explained in Section 3.7.3, the amount of negative GDD provided by the Treacy grating compressor when the pulse duration was minimized was approximately -0.320 ps².

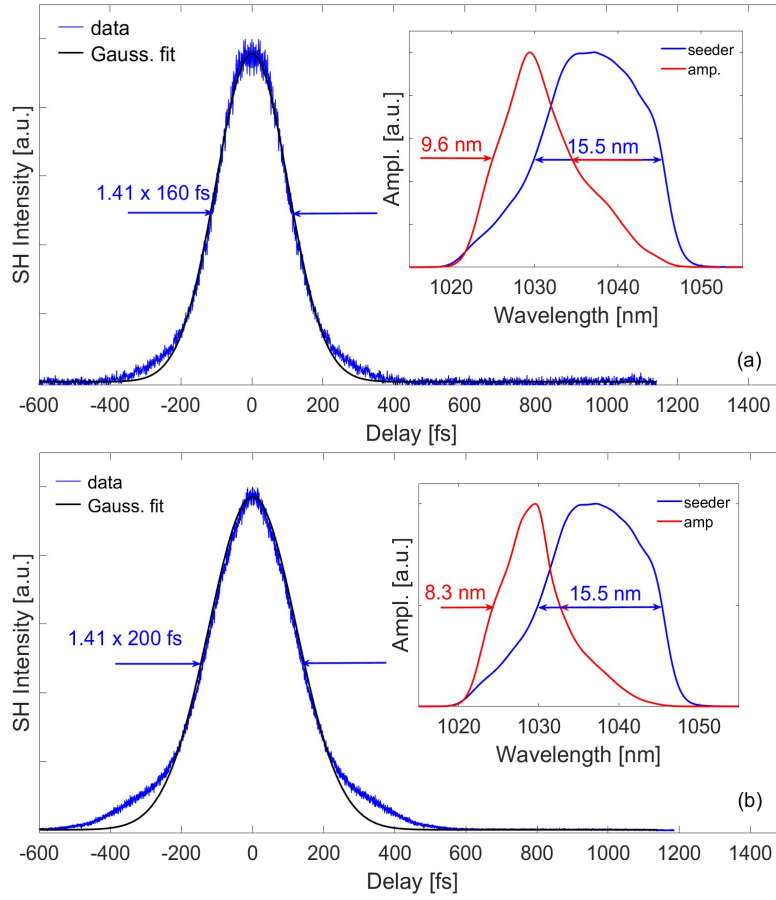


FIGURE 3.34: Autocorrelation trace of the amplified pulses at the central output wavelength of 1035 nm for an incident pump power of 6.2 W and seeder input power of 15 mW. In the inset are shown the corresponding optical spectrum of the seeder (blue) and the amplified spectrum (red). (b) Autocorrelation trace of the amplified pulses at the central output wavelength of 1035 nm for an incident pump power of 8.7 W and seeder input power of 15 mW. In the inset are shown the corresponding optical spectrum of the seeder (blue) and the amplified spectrum (red)

If we put our value of GDD and $\tau_0 = 200$ fs, we obtain almost 5 ps, which is a chirped pulse duration in good agreement with the specifications of the fiber laser seeder.

To determine the theoretical amount of dispersion that caused the pulse broadening, the formula can be inverted:

$$GDD = \frac{\tau_0^2}{4 \ln 2} \cdot \sqrt{\left(\frac{\tau}{\tau_0}\right)^2 - 1} \quad (3.22)$$

If we solve eq. 3.22 we get exactly -0.360 ps², fairly close to our estimation.

These results demonstrate the robustness of the amplifier-compressor chain in preserving the temporal quality of broadband ultrafast pulses, even in the presence of gain narrowing, with a maximum average output power after the compressor of 1.5 W. At 40 MHz rep. rate, this corresponds to a pulse energy of ≈ 37 nJ, yielding according to eq. 3.15 a peak power of ≈ 190 kW which is already sufficient for very efficient harmonic generation, material processing and nonlinear optic applications.

To evaluate the B-integral we can exploit eq. 3.16 taking into account the "new" intensity, being careful that we have to take into account the maximum intensity during the amplification process which means with 5 ps pulse duration. And the corresponding peak power became ~ 8 kW (eq. 3.15) so almost 1/10 respect the Pavia setup which means that since the mode dimension in the crystal, and the crystal length were the same, the B-integral is almost 0.06 so $\ll 1$. This means that the self phase modulation effect is negligible during the propagation in the four-pass amplifier

Chapter 4

Oscillators experiments

The final stint of my PhD was devoted to the investigation of the potential of the tapered-diode module for direct pumping of fs oscillators. My aim was to try to exploit the high brightness of the pump module and try to circumvent the issue related to the polarization of the pump beam which is almost equally split between two orthogonal directions. Therefore, as discussed in Chapter 2, the choice of the gain medium had to meet two main criteria: efficient pump absorption at 980 nm, and significant absorption along both optical axes. Among the materials available in our laboratory, we had few AR-coated Yb:CaF₂ crystals with different lengths and doping concentrations: namely one crystal of 3 mm length and two of 2 mm, all doped at 5%.

Yb:CaF₂ appeared to be a promising candidate, as its peak absorption cross-section is centered around 980 nm (see Fig. 2.7). Additionally, being an isotropic material, Yb:CaF₂ exhibits polarization-independent absorption, which simplifies the pump alignment and improves efficiency. Its broad emission bandwidth also makes it highly suitable for generating ultrashort pulses.

At the beginning, since the optimal crystal length to realize an efficient pump absorption was ~ 4 mm, we decided to put the two 2-mm samples close to each other, thus obtaining an equivalent crystal length of 4 mm. However, both the 2 mm crystals, were partially damaged, in particular, the AR coating of the crystals facets looked locally damaged. Further degradation was observed during my experiments issue significantly limited the performance of the oscillator in the Mode-Locking regime. After one of the two 2 mm crystals ultimately break up during testing, we were forced to use the 3 mm

crystal.

In addition to Yb:CaF₂, we had at our disposal a 10%-doped, 5.2-mm-long Yb:YLF crystal, with polished facets, suitable to be put in a resonator oriented at Brewster angle. As discussed in Section 2.6, Yb:YLF is particularly appealing due to its favorable absorption cross-sections at 980 nm, which closely match the emission spectrum of our tapered diode module (see Section 1.2), ensuring efficient pump absorption for both diodes.

Since on paper and based on the results presented in literature, Yb:CaF₂ is expected to sustain shorter pulses than Yb:YLF, initial tests of the oscillator were carried out using this material.

4.1 Yb:CaF₂ laser

4.1.1 Yb:CaF₂ CW Experiments

The initial tests were carried out using the equivalent 4 mm crystal fixed on a heat sink water cooled at 20°, inserted in an X-shaped cavity designed to be easily adapted for future mode-locking operation by introducing dispersive elements such as prisms or GTIs and a SESAM. The CW cavity layout is shown in Fig. 4.1.

The first design step focused on optimizing the pump beam spot. The output $1/e^2$ pump waist was approximately 400 μm , which was focused to about 25 μm by an achromatic lens (L1, $f = 30$ mm, see Fig. 4.1). This spot was then imaged into the gain medium using a 1:1 telescope composed of lenses L2 and L3. The corresponding pump beam confocal parameter

$$b = 2n \frac{\pi w_p^2}{\lambda_p} \frac{1}{M_p^2} \simeq 4 \text{ mm}$$

calculated assuming a refractive index $n = 1.43$ for Yb:CaF₂ and a $M_p^2 = 1.5$ for the pump beam, was well matched to the composite crystal length.

We also carried out a direct measurement of the pump beam spot scanning a CCD camera along the focal plane of lens L3. The results obtained at the maximum pump

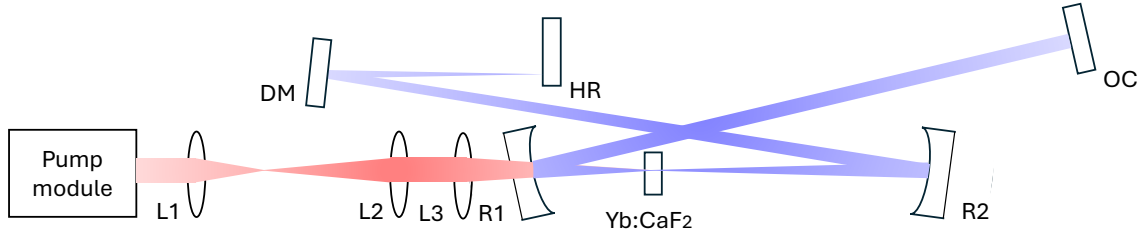


FIGURE 4.1: Schematic layout of the Yb:CaF₂ CW oscillator. DM: dichroic mirrors; HR: high-reflectivity mirror; OC: wedge output coupler; L1: $f = 30$ mm; L2, L3: $f = 100$ mm; R1: Dichroic spherical mirror (HT @ 980 nm – HR @ 1050 nm), $R = -100$ mm; R2: spherical mirror, $R = -250$ mm; distances: R1–OC = 380 mm, R2–HR = 430 mm, R1–R2 = 230 mm.

power are shown in Fig. 4.2. The waist dimensions along the x and y axes were approximately $25\mu\text{m}$ and $33\mu\text{m}$, respectively, with an overall M^2 factor below 1.7, relatively close to the expected value of ~ 1.5 .

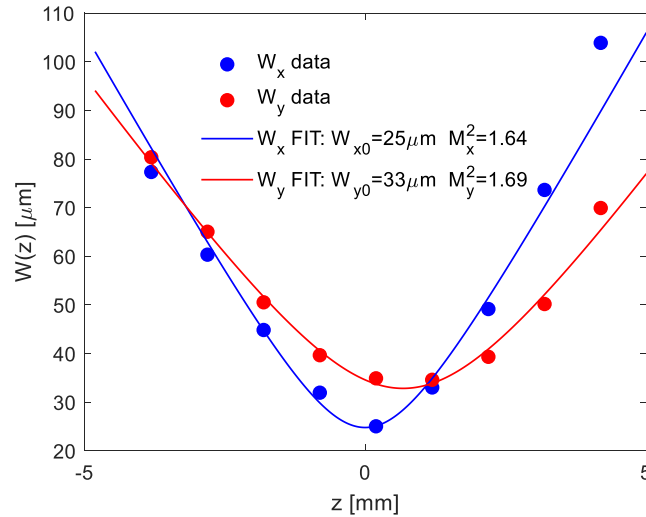


FIGURE 4.2: Beam quality measurement of the pump diode beam with the crystal mounted on the heat-sink older taking into account the condition under thermal load; pump power: 9.5 W.

Our goal is to exploit the diode brightness in order to maximize the fluence in the active medium by tightly focusing the pump beam. As discussed in [57], [17], this is a crucial aspect for femtosecond ML stabilization against Q-Switching instabilities when using a SESAM. For this reason, once it was determined that a 4 mm crystal was long enough to efficiently absorb the pump, we chose the smallest possible pump spot while

keeping the confocal parameter comparable with the crystal length, to ensure good overlap between the pump and cavity modes.

According to [17], the intracavity pulse energy E_p must satisfy the following condition to ensure a stable ML:

$$E_p > \sqrt{\left(\frac{g\tilde{\xi}^2 E_G}{2}\right)^2 + E_G E_S \Delta R} - \frac{g\tilde{\xi}^2 E_G}{2} \quad (4.1)$$

where E_G , E_S are the saturation energies of the gain medium and SESAM, respectively ($E_{G/S} = F_{sat,G/S} A_{G/S}$), g is the saturated gain coefficient of the active medium (which is set by the cavity losses at the laser threshold), ΔR is the modulation depth of the SESAM, and $\tilde{\xi} = \Delta\nu_p / \Delta\nu_g$ is a factor that measures the fraction of the total available gain bandwidth that is actually exploited by the ML pulse, and it is typically ranging from 0.3-0.7.

Design-wise, the fluence on the SESAM must be high enough to lower the ML threshold, but not excessive, to avoid optical damage in case of Q-switching instabilities. Using the relations given in eq. 4.1, and predicting the laser average output power with 9 W of pump, we identified a minimum mode size on the SESAM in the range of 70–100 μm to both preserve the SESAM and ease the ML regime starting.

We also aim for a relatively low repetition rate, around 100 MHz. A lower repetition rate increases the pulse energy, which facilitates ML initiation according to eq. 4.1, but excessively low values would lead to very long cavities, making the setup bulky and more sensitive to misalignment and diffraction losses.

Once these design constraints are fixed and the X-folded cavity architecture is selected, we must decide whether to operate in the first or the second stability zone. The first corresponds to the confocal scheme, in which both curved mirrors re-collimate the cavity mode and their distance is approximately equal to $(R_1 + R_2)/2$. The second corresponds to the case where the second curved mirror (R_2) is used to directly refocus the cavity mode onto one of the end mirrors, which in our case is the HR/SESAM. We opted for the second configuration for two main reasons:

- it allows us to save one curved mirror (and its associated losses) that would otherwise be required to refocus onto the SESAM, and, more importantly,
- it is compatible with the single-prism dispersion compensation scheme that we intend to employ[47]. Conversely, a confocal cavity requires a prism pair, introducing additional losses and alignment complexity.

In the single-prism arrangement, the angular dispersion of the only prism present in the cavity causes different frequencies to follow different optical axes throughout the cavity, in contrast to the prism-pair setup. If the cavity optics are properly chosen, there is an intersection point X, which is generally not a beam waist of the Gaussian cavity mode, where the different rays corresponding to different "colors", crosses. The distance between the real prism and this crossing point "X" determines the amount of GVD in the cavity. The position of the "X" point can be determined with a simple ABCD matrix calculation, as it is shown in Ref. [47]. In case of an X-folded cavity geometry set to work in the 2nd stability region, as in our case, the position "X" happens to be typically very close to the curved mirror R1, allowing to use the single prism in the cavity arm from R1 to the OC (see Fig. 4.6).

The main drawback of the single-prism setup is that spectral components are spatially dispersed transversally inside the active medium and the finite dimension of the gain volume determines a spectral filtering effect, the more dispersive the prism, the more significant this filtering effect. Indeed, the effective bandwidth

$$\Delta\nu_{eff} \approx \frac{w_g}{|dx/d\lambda|} \quad (4.2)$$

is proportional to the beam waist in the active medium w_g and is inversely proportional to the spatial dispersion $dx/d\lambda$ that depends on the prism material.

Once the general design constraints were defined, a detailed ABCD matrix analysis was carried out to determine the optimal cavity geometry and to ensure proper matching between the cavity mode and the pump mode in the active medium. Particular attention

was devoted to the distances between the curved mirrors and the end mirrors, as these directly define the mode sizes at the critical positions of the cavity.

The length of the arm between the first curved mirror (R1) and the output coupler (OC) plays a crucial role in fixing the dimension of the cavity mode in the active medium, since increasing this distance leads to a larger waist at the OC, but simultaneously reduces the cavity mode waist in the crystal. At a certain point, if the cavity mode becomes significantly smaller than the pump mode, single transverse mode operation of the laser is no more guaranteed, and the ML regime becomes unstable.

In our operating conditions, the optimal length of this cavity arm was around 400 mm, while the resonator started to show the tendency to multi-transverse mode operation when the length exceeded 600 mm.

On the opposite side of the cavity, the mirror R2 (see Fig. 4.1) act as a lens of focal length $f_2 = R_2/2$ and re-images the cavity mode in the active medium on the HR mirror (that is replaced by the SESAM when ML regime is required). The magnification factor is simply given by the ratio between the length of the R2-HR segment divided by the distance between the active medium (whose position coincides with the cavity mode waist) and mirror R2, according to the well known Newton's law of lenses. We selected a curved mirror $R_2 = -250$ mm. Since we wanted a magnification factor of about 2.5 of the size of the mode in the active medium to reach about $80 \mu\text{m}$ beam waist on the HR/SESAM, we set the length of the segment R2-HR to about 430 mm and consequently the optimal distance between the active medium and R2 for cavity stability was around 180 mm.

Figure 4.3 summarizes the results of the ABCD matrix simulations, showing the evolution of the beam waist along the cavity for different positions of the R2 mirror. Positive values indicate an increase in the distance between R1 and R2, while negative values correspond to its reduction. The calculated mode radii were approximately $35\text{ }\mu\text{m}$ inside the crystal (Fig. 4.3(a)), $330\text{ }\mu\text{m}$ at the OC (Fig. 4.3(b)), and $90\text{ }\mu\text{m}$ at the HR/SESAM (Fig. 4.3(c)). These simulations also take into account the small incidence angle of $\sim 2^\circ$ (full angle) at the spherical mirrors, which introduces a slight difference between the sagittal and tangential planes but does not significantly affect the mode sizes at the relevant positions.

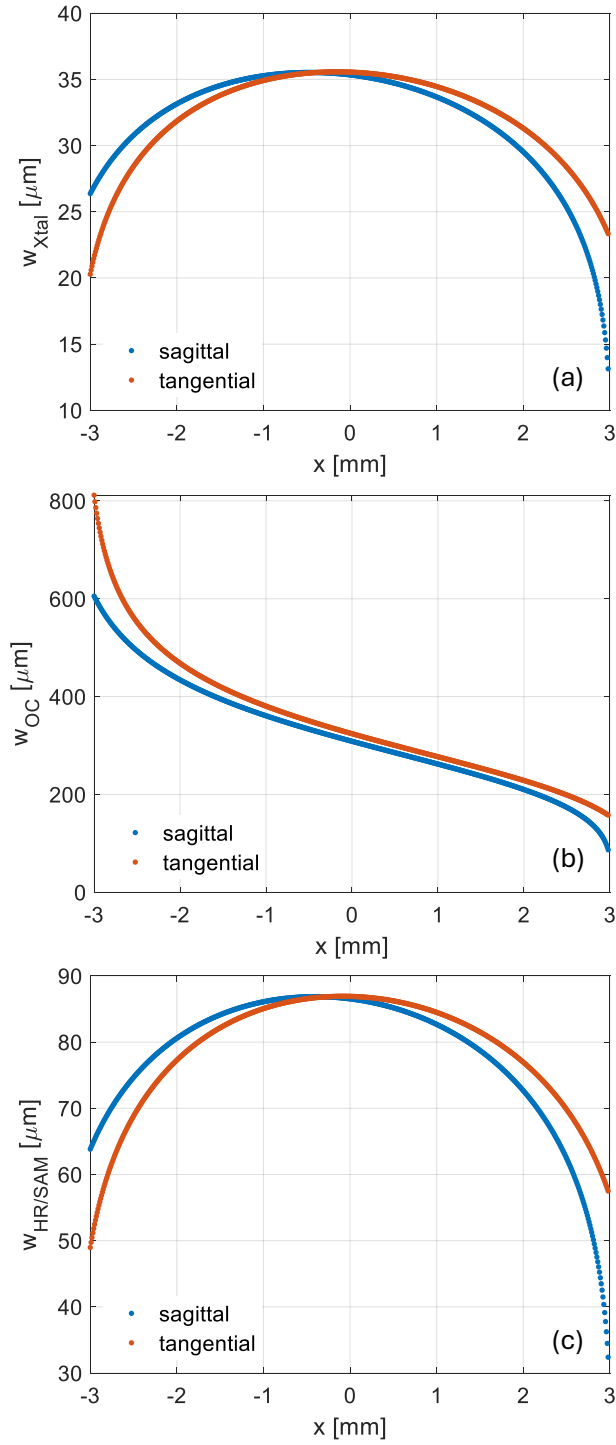


FIGURE 4.3: ABCD matrix simulation of the cavity: (a) laser waist in the crystal, (b) waist at the output coupler (OC), and (c) waist at the HR/SAM mirror. The abscises axis measures the displacement of mirror R2 from its reference position in Fig. 4.1. A positive value indicates that the mirror is farther from the crystal, while a negative value means it is closer.

Once the cavity design was optimized, the next step was to characterize the laser in CW regime. As shown in Figure 4.4, we measured the output power as a function of the absorbed pump power for different output coupler transmissions. We measured the incident pump power at the pump module output and the residual transmitted pump power after the dichroic mirror (see DM in Fig. 4.1). The absorbed pump power was calculated as the difference between these two values. Four OCs with transmissions of 1.6%, 5%, 10%, and 16% were tested. Despite the tapered diode beam spatial characteristics depend in the driving current, the measurement shown in Fig. 4.4 present a reasonably linear dependence of the output power from the absorbed pump power. Only close to the maximum absorbed pump power, we observed a slight roll-off of the power, likely due to thermal effects.

As expected, the lowest slope efficiency (about 38%) was measured with the lowest transmission output coupler. A best slope efficiency of about 50% was obtained with the $T_{oc} = 5\%$ and 10%. Some parasitic losses at higher output coupling limited the attainable slope efficiency. Indeed, we observed a drop in the slope efficiency with the $T = 16\%$ output coupler. A maximum output power of 3.1 W was obtained at about 7.3 W absorbed pump power with the $T = 5\%$ output coupler.

The CW characterization we performed with different output couplers can be useful to assess the resonator losses and the oscillator asymptotic efficiency. When the quasi three level laser operates above the threshold and the reabsorption losses are saturated, the output power depends on the absorbed pump power in the same way as in the 4-level materials [50]

$$P_{\text{out}} = \eta_0 \frac{\lambda_p}{\lambda_L} \frac{-\ln(R_{OC})}{\delta - \ln(R_{OC})} (P_{\text{abs}} - P_{\text{th}}). \quad (4.3)$$

where

- λ_L and λ_p are the laser and pump wavelengths, respectively;
- δ are the resonator losses;
- R_{OC} is the output coupler reflectivity;

- η_0 is the asymptotic efficiency of the laser (the one that would be reached if the cavity losses δ are negligible with respect to the output coupling losses given by $\ln(1/R_{oc})$).
- P_{th} is the absorbed pump power at the threshold of the laser oscillation.

Consequently, the effective slope of the linear curve can be written as:

$$\eta_{\text{slope}} = \eta_0 \frac{\lambda_p - \ln(R_{oc})}{\lambda_L \delta - \ln(R_{oc})}. \quad (4.4)$$

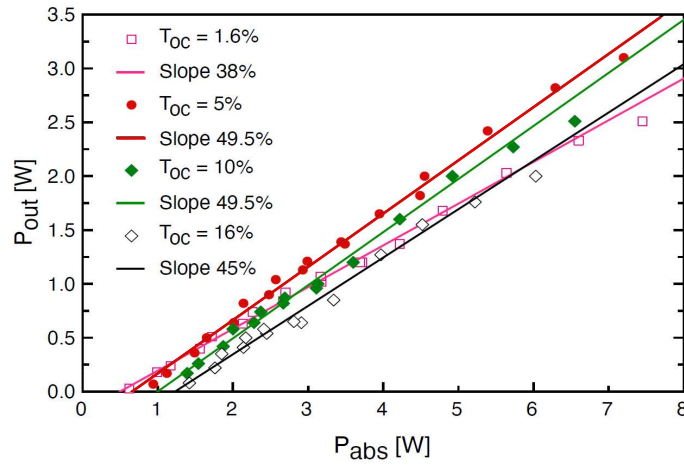


FIGURE 4.4: Measured output power as a function of absorbed pump power for different output coupler transmissions. The linear fit to each dataset shows the extracted slope efficiency. The data confirm the trade-off between threshold and output coupling.

By fitting the measured slope efficiency of the laser as a function of the output coupling losses (hence performing the so-called Caird analysis [50], one can determine the cavity losses (excluded the reabsorption losses) and the asymptotic efficiency η_0 . Since output coupling-dependent losses are not included in this model, we excluded from the fit the experimental point relative to the $T = 16\%$ output coupler. The resulting fit, shown in Fig. 4.5, yields an intrinsic efficiency η_0 of about 55% and extremely low round-trip losses of approximately 0.5%. This is consistent with the observation that a significant output power of 2.5 W was achieved even with the lowest OC transmission ($T = 1.6\%$). For our experiments we decided to use the OC which gave best performances ($T_{oc} =$

5%), with eventually the possibility to use even lower OC if it was difficult to start or stabilize the ML.

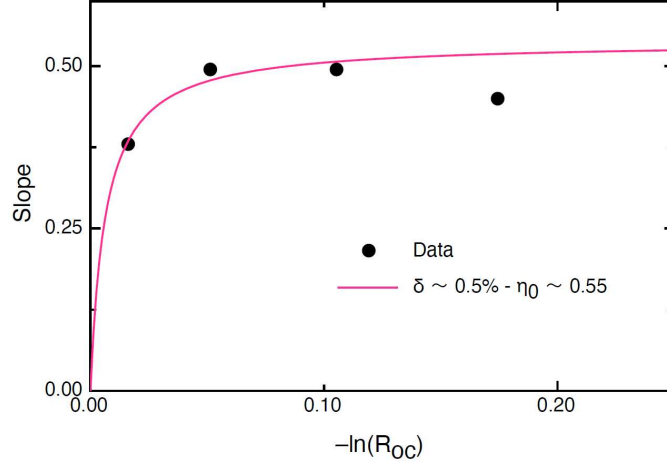


FIGURE 4.5: Caird plot: slope efficiency as a function of output coupler transmission. Black dots represent the experimental data; the solid line is the theoretical fit based on Eq. 4.4. The fitted intrinsic slope efficiency and round-trip losses are also indicated.

4.1.2 Mode-Locking results with a single SF10 prism

Starting from the CW configuration, the mode-locked (ML) setup was similar, as shown in Fig. 4.6. The output coupler (OC) with 5% transmission was used, the HR end-cavity mirror was replaced with a SESAM, and a single SF10 prism was introduced as a dispersive element. The distance between R1 and the OC was fixed at 380 mm, while the position of the prism was adjusted to provide sufficient negative group delay dispersion (GDD) to compensate for the positive GDD introduced by the cavity.

According to ABCD matrix simulations, the virtual position of the prism was located about 10 cm after the crystal towards the OC (see Fig. 4.7). This means that the maximum distance between the virtual prism and the actual prism could be approximately 25 cm. This corresponds to a maximum negative dispersion per roundtrip of $\sim -5400 \text{ fs}^2$. Considering that the positive group velocity dispersion introduced by SF10 glass is approximately $+110 \text{ fs}^2/\text{mm}$ at 1040 nm [58], at the maximum possible insertion corresponding to a physical path inside the SF10 prism of about 15 mm (corresponding to $\sim 30 \text{ mm}$ per

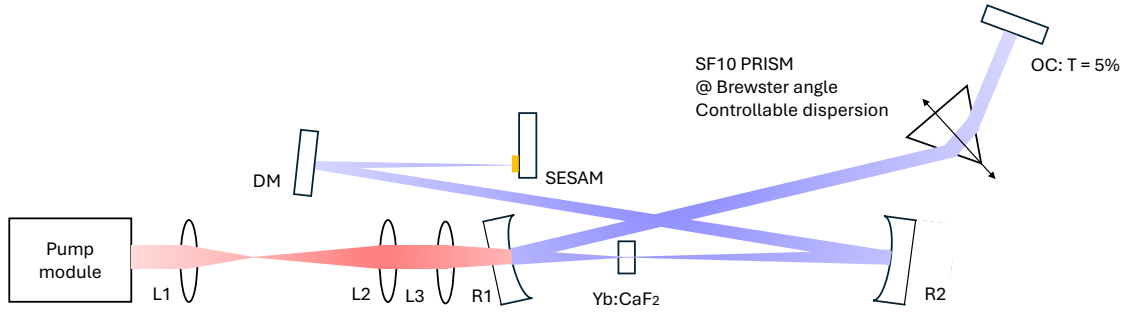


FIGURE 4.6: Schematic layout of the Yb:CaF₂ mode-locked oscillator. DM: dichroic mirrors; OC: wedge output coupler; L1: $f = 30$ mm; L2, L3: $f = 100$ mm; R1: dichroic spherical mirror (HT @ 980 nm, HR @ 1050 nm), $R = -100$ mm; R2: spherical mirror, $R = -250$ mm. Distances: R1-OC = 380 mm, R2-SESAM = 430 mm, R1-R2 = 230 mm.

round trip), the maximum positive dispersion that can be added is $\sim +3300 \text{ fs}^2$. This shows that we can broadly tune the net intracavity GVD.

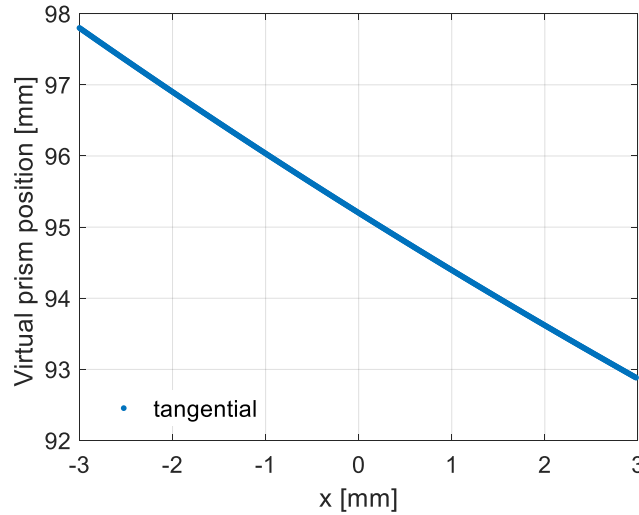


FIGURE 4.7: Simulated position of the virtual prism inside the cavity. The reference is set in the position of mirror R1, with positive value corresponding to the direction towards the OC and negative, towards the active medium (refer to Fig. 4.6). The abscises axis measures the displacement of mirror R2 from its reference position. A positive value indicates that the mirror is farther from the crystal, while a negative value means it is closer.

For instance, the use of a fused silica (FS) prism, would be un-practical in our setup, since we can not increase too much the distance between R1 and OC if we want to guarantee single transverse mode operation for our laser. Indeed, FS dispersion power is

approximately 5 times lower than that SF10. This means that, for the same insertion distance of 25 mm, the maximum achievable negative GDD is only about -1200 fs^2 [59], which is not sufficient to balance the intracavity dispersion over the full spectral range of interest.

The SF10 prism was mounted on a micrometer translation stage for fine adjustment of the GDD. Additionally, the prism set the polarization of the laser in the plane parallel to the optical table, since it was Brewster-cut.

In the path from R2 towards the SESAM, we placed a dichroic mirror (DM) that transmitted the residual pump that was not absorbed by the active medium and was reflected by mirror R2. In this way we both avoided unnecessary heating of the SESAM because of the residual pump power impinging on it, and we prevented dangerous back-reflections of the pump towards the tapered-diodes. The total cavity length was approximately 1.05 m, corresponding to a pulse repetition rate of $c/(2l_c) \approx 140 \text{ MHz}$ (see Fig. 4.8).

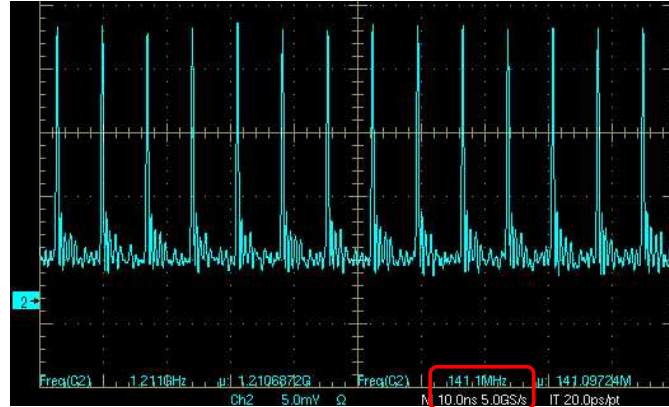


FIGURE 4.8: Pulse train measured with a fast photodiode and oscilloscope.

The measured pulse spectrum and autocorrelation trace are shown in Fig. 4.9. The central wavelength was around 1040 nm with a FWHM bandwidth of approximately 8 nm. The average output power was 3 W, corresponding to a pulse energy of about 20 nJ. The autocorrelation trace yielded a pulse duration of 175 fs with a time-bandwidth product (TBP) of approximately 0.38, close to the Fourier-transform limit of ~ 0.32 for soliton sech^2 -shaped pulses. In this configuration, the estimated negative GDD was about -1200

fs². Given the pulse energy and measured pulse duration, we estimated a peak power exceeding 100 kW. Results in literature [37], suggest that Yb:CaF₂ can support much shorter pulses, well below the 100-fs limit. One of the possible limitations to the minimum attainable pulse duration in our setup may arise from the bandwidth filtering effect taking place in the active medium, due to the chromatic dispersion induced by the single prism configuration, as explained in [17].

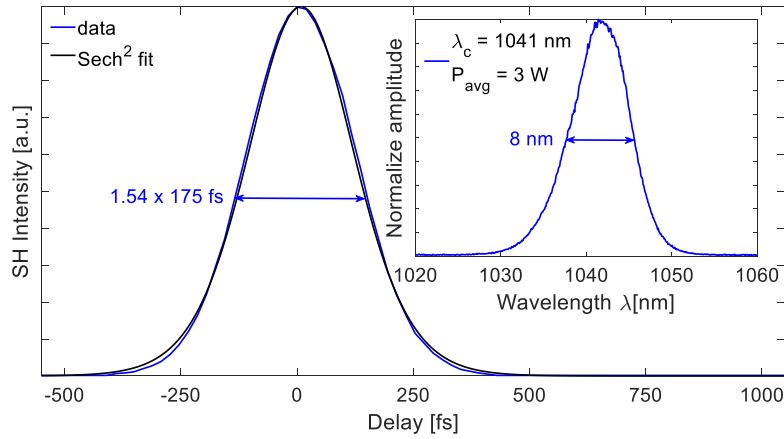


FIGURE 4.9: Autocorrelation trace of laser pulses at the central output wavelength of 1041 nm for an incident pump power of 9.5 W. In the inset are shown the corresponding optical spectrum the SF10 prism setup.

This effect can be quantified using ABCD matrix calculation once it is known the angular dispersion given by the prism, and the position of the virtual prism with respect to the active medium in the cavity. In this way, it is possible to calculate the "off-axis" displacement of the pulse chromatic components in units of, e.g., μm of lateral displacement per nm of spectrum. Eventually, the gain channel induced by the pump in the active medium works as a sort of soft spectral filter with an equivalent bandwidth that depends on the pump beam waist. The resulting lateral dispersion was estimated to be approximately $2.4 \mu\text{m}/\text{nm}$ in our case, indicating that a spectral component of the pulse bandwidth located at 1 nm distance from the peak of the spectrum would be laterally displaced from the pump beam axis by $2.4 \mu\text{m}$ within the laser crystal. For an 8 nm bandwidth, this corresponds to a total spatial separation of about $20 \mu\text{m}$.

$$\Delta x = \frac{dx}{d\lambda} \Delta \lambda. \quad (4.5)$$

This spatial spread value is comparable to the beam waist inside the crystal, implying that the chromatic dispersion may limit the maximum achievable pulse bandwidth in this setup. Therefore, while the SF10 prism compensates the cavity GDD for sub-200 fs pulses, it is not ideal for generating significantly broader spectra that could allow even shorter pulse durations.

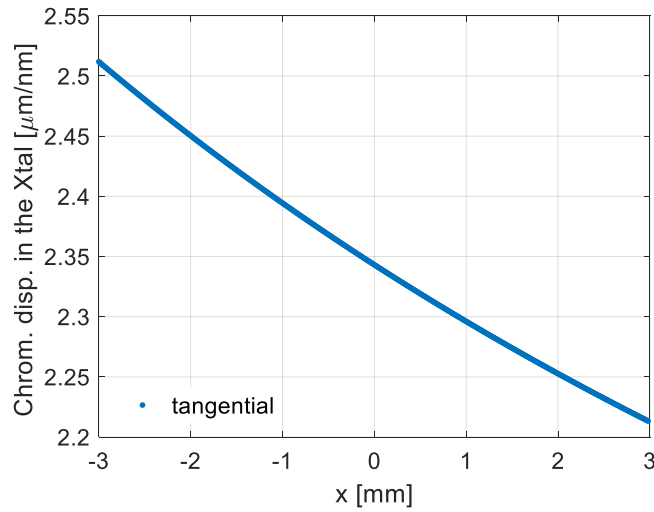


FIGURE 4.10: Simulated chromatic dispersion in the gain medium due to the virtual prism as a function of the distance between curved mirrors R1 and R2, the "0" position being the optimal distance used in the experiments. The abscises axis measures the displacement of mirror R2 from its reference position in Fig. 4.6. A positive value indicates that the mirror is farther from the crystal, while a negative value means it is closer.

4.1.3 Mode-locking with Fused Silica Prism Experiments

In order to overcome the possible limitation due to the aforementioned spectral filtering effect, we also tested a cavity employing a single FS prism. In this regard, the main advantage of FS is its much lower dispersion compared to SF10, which results in significantly reduced spatial chirp. Additionally, according to our experience, the optical quality of FS glass is typically better than SF10 and the lower dispersion helps minimizing the insertion losses at Brewster angle, since typically commercially available isosceles prisms

for dispersion compensation are cut for optimal performance at 800 nm wavelength for Ti:Sapphire fs lasers. Of course, the negative GDD introduced by a prism pair depends on the distance between the two prisms and the dispersion of the material, so that it is necessary to account for the lower material dispersion by increasing the prisms distance accordingly. This is true also in case of a single prism arrangement, and in our specific case it means that we have to increase the length of the R1-OC arm of the resonator.

In general, for the same wavelength and prism separation, the negative GDD introduced by SF10 is about four times larger than that of fused silica, thus requiring a significantly larger separation. Under these conditions, the laser beam waist in the active medium becomes $\sim 30 \mu\text{m}$, and we observed a strong tendency for the laser to operate in a multi-spatial mode regime, which makes stable ML regime impossible.

Moreover, unfortunately, at this stage, one of the two Yb:CaF₂ crystals that we employed to obtain the equivalent 4-mm-long active medium was damaged. Therefore we decided to replaced the remaining crystal with the 3-mm-long sample we still had at our disposal in the lab. To overcome the issue related to the excessive length of R1-OC cavity arm, we opted for the "hybrid" solution presented in Fig. 4.11). A pair of Gires–Tournois Interferometric mirrors (GTIs) was added, providing two reflections with -250 fs^2 GDD per bounce. The fine adjustment of the residual negative dispersion needed for the soliton ML was done with the single FS prism.

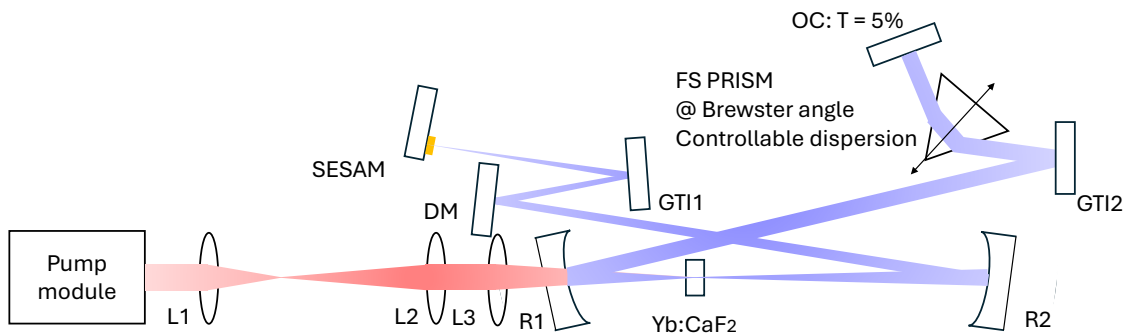


FIGURE 4.11: Schematic layout of the Yb:CaF₂ mode-locked oscillator. DM: dichroic mirrors; OC: wedge output coupler; L1: $f = 30 \text{ mm}$; L2, L3: $f = 100 \text{ mm}$; GTI1, GTI2: -250 fs^2 GDD each; R1: dichroic spherical mirror (HT @ 980 nm, HR @ 1050 nm), $R = 100 \text{ mm}$; R2: spherical mirror, $R = 250 \text{ mm}$. Distances: R1–OC = 390 mm, R2–SESAM = 430 mm, R1–R2 = 230 mm.

The results (spectra at different central wavelengths and the corresponding autocorrelation traces) are shown in Fig. 4.12. In particular, we analyzed the performance at 1040 nm, 1044 nm, and 1050 nm. Clearly, the average output power tends to increase towards the red side of the spectrum, starting from 2 W at 1040 nm, rising to 2.5 W at 1044 nm, and reaching 3 W at 1050 nm.

For the latter two wavelengths, we observed narrower spectra of about 4–5 nm FWHM, corresponding to Fourier transform-limited pulse durations of around 300 fs (time-bandwidth product, TBP, approximately 0.32). In contrast, at 1040 nm, the spectrum was broader ($\Delta\lambda = 8$ nm), yielding a shorter pulse duration of approximately 190 fs and a slightly higher TBP of 0.38, similar to the result obtained with the SF10 prism setup (see Fig. 4.9).

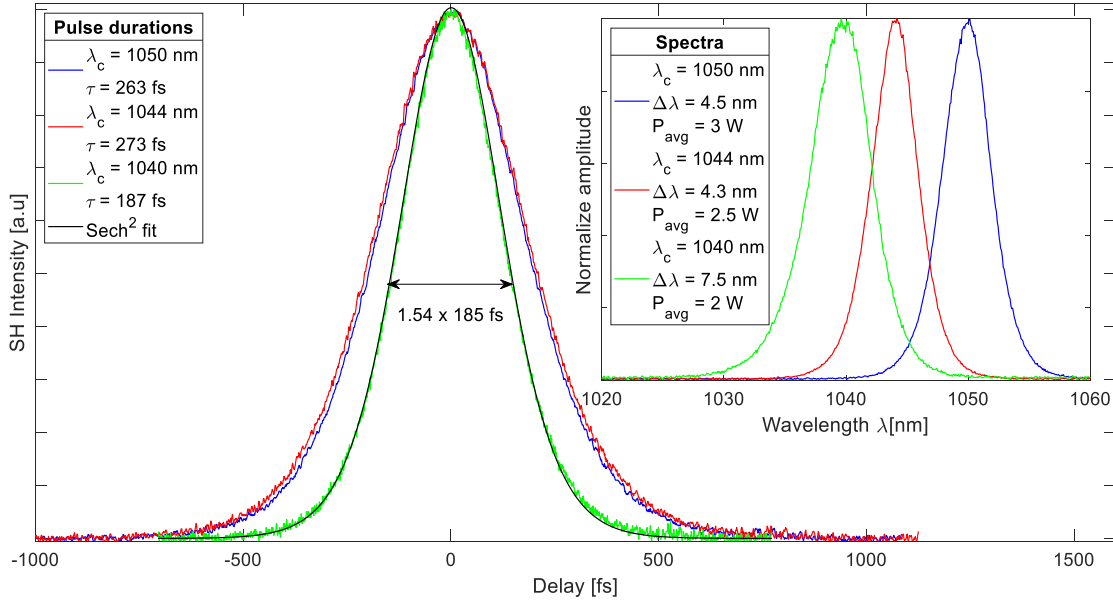


FIGURE 4.12: Measured autocorrelation traces and corresponding optical spectra in the inset at different central wavelengths (1040,1045,1050 nm). Incident pump power 9.5 W

4.1.4 Mode-locking experiments with only GTIs

After completing the measurements with the FS prism hybrid setup, since we did not improve the performance obtained with the SF10 prism, we opted for a simplified cavity design using only GTIs to introduce the required GDD. In particular, we employed three GTI mirrors to achieve a total GDD of $\sim -1200 \text{ fs}^2$: two GTIs with -250 fs^2 each, and one

additional GTI with -100 fs^2 , ensuring that each mirror was hit twice per round trip. The optical layout is shown in Fig. 4.13, where all intra-cavity distances were kept fixed as before.

We also introduced a Brewster glass plate (BP) positioned as close as possible to the SESAM. The BP not only ensures the polarization of the laser in the plane of the optical table, but also might contribute to spectral broadening via SPM.

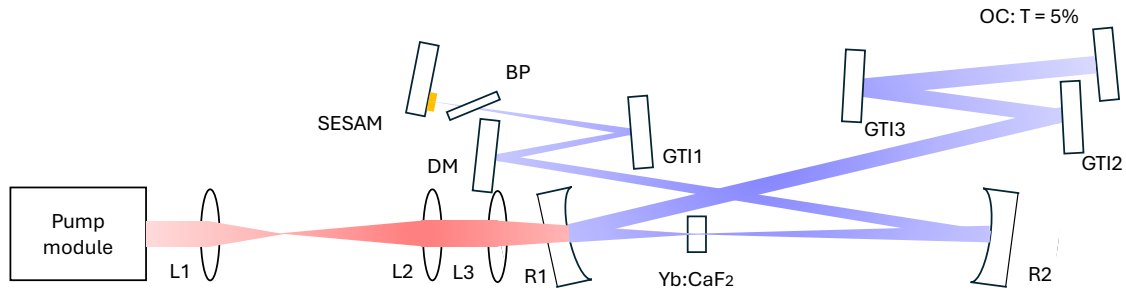


FIGURE 4.13: Schematic layout of the Yb:CaF₂ mode-locked oscillator. DM: dichroic mirrors; OC: wedge output coupler; L1: $f = 30 \text{ mm}$; L2, L3: $f = 100 \text{ mm}$; GTI1, GTI2: -250 fs^2 GDD each; GTI3: -100 fs^2 ; BP: Brewster glass plate; R1: dichroic spherical mirror (HT @ 980 nm , HR @ 1050 nm), $R = -100 \text{ mm}$; R2: spherical mirror, $R = -250 \text{ mm}$. Distances: R1-OC = 380 mm , R2-SESAM = 430 mm , R1-R2 = 230 mm .

At first, we evaluated the spatial mode quality of the laser output. As shown in Fig. 4.14, the beam waist was measured to be approximately $33 \times 39 \mu\text{m}^2$, with M^2 values of 1.0 and 1.2 along the x - and y -axes, respectively. The slight ellipticity may be attributed to the residual astigmatism introduced by the curved mirrors R1 and R2 and that could not be compensated since the Yb:CaF₂ crystal could not be placed at the Brewster angle. Overall, the beam quality was excellent and close to the diffraction limit as expected.

Unfortunately, before we could measure the autocorrelation trace to retrieve the pulse duration, also the 3-mm Yb:CaF₂ crystal was damaged. Nevertheless, we were able to record the output spectrum, which is reported in Fig. 4.15. The spectrum was centered at 1049 nm with a FWHM of approximately $10\text{-}11 \text{ nm}$, corresponding to an estimated pulse duration of 120 fs assuming a TBP of 0.35, similar to the one obtained previously in this setup. This is the broadest spectrum achieved among all tested configurations. The

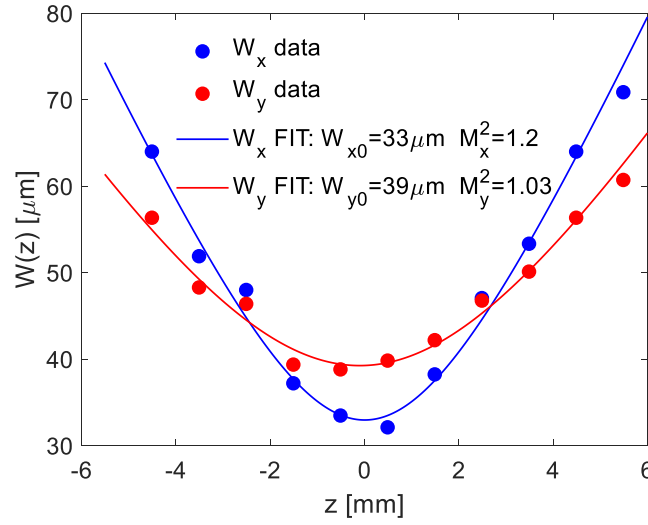


FIGURE 4.14: Measured beam profile and M^2 parameters for the GTI-based setup.

average output power was 3 W.

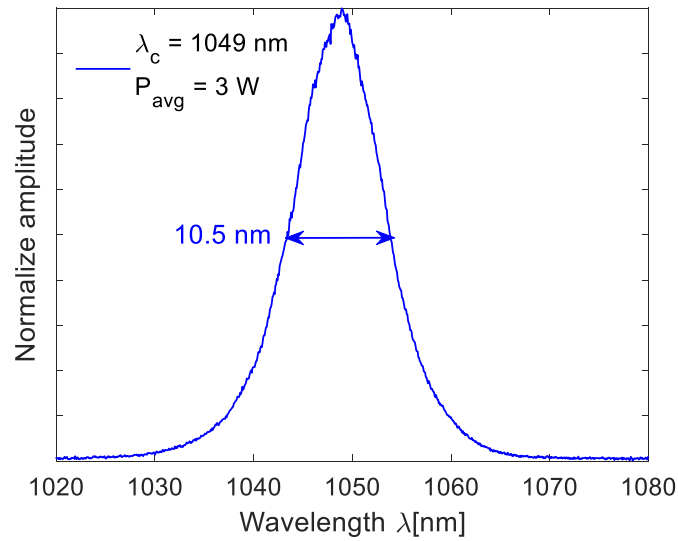


FIGURE 4.15: Measured spectrum of the mode-locked laser centred at 1049 nm for an incident pump power of 9.5 W using the GTI-only cavity configuration.

If compare our results with literature about fs Yb:CaF₂[37],[17],[60], we are clearly far from the best possible results at least in terms of pulse duration. A part from obvious concerns about the actual quality of the crystal we had in the lab, the major limiting factor that we could identify in our setup might be related to the spectral response of the GTI

mirrors we had at our disposal.

The GTIs used were bought several years ago from Layertech GmbH, and their specifications were no longer available on the manufacturer website. However, we compared their expected behavior with the current GTIs available from the same supplier, shown in Fig. 4.16. While GTIs with large GDD per bounce (e.g., -1300 fs^2 and -2000 fs^2) exhibit narrow operational bandwidths and non-flat GDD profiles, the ones used in our setup (-250 fs^2 and -100 fs^2) should not significantly restrict the bandwidth due to their relatively flat dispersion across the relevant spectral range.

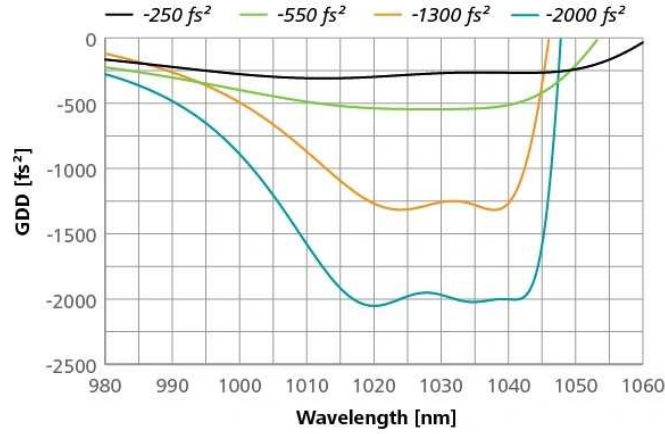


FIGURE 4.16: GDD spectra of GTI-mirrors with different GDD values. [61]

Although the GTI-only configuration provided the broadest spectra among all tested setups, further optimization was hindered by crystal damage before pulse characterization could be completed. Spectral filtering by the cavity mirrors and GTIs does not appear to limit the bandwidth significantly; only above 1050 nm the negative GDD start to drop. Given the results from similar setups using Yb:YLF (see Sec. 2.6), and considering the excellent average output power observed here (up to 3 W), we conclude that the main bandwidth limitation likely stems from the crystal's degraded condition rather than from the SESAM or the optics. Future tests with a high-quality Yb:CaF₂ crystal could provide better results.

4.2 Yb:YLF femtosecond laser

4.2.1 Yb:YLF CW Experiments

As with the Yb:CaF₂ laser, we began by characterizing the system in CW regime. The cavity layout was essentially unchanged: the pump beam waist and the cavity arm lengths remained the same to maintain the optimized mode matching.

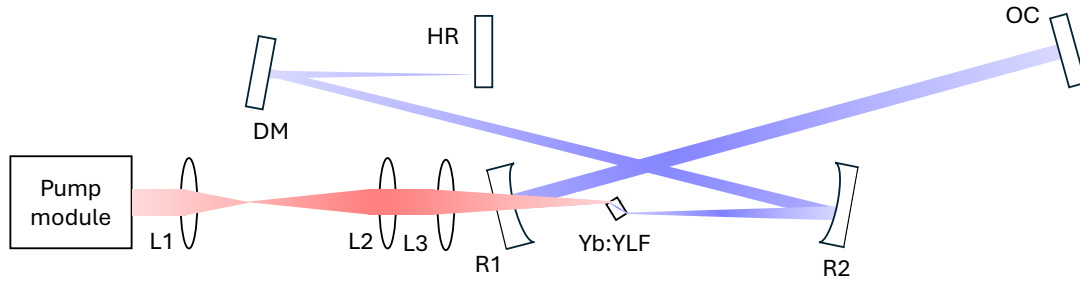


FIGURE 4.17: Schematic layout of the Yb:YLF CW oscillator. DM: dichroic mirrors; OC: wedge output coupler; L1: $f = 30$ mm; L2, L3: $f = 100$ mm; R1: dichroic spherical mirror (HT @ 980 nm, HR @ 1050 nm), $R = -100$ mm; R2: spherical mirror, $R = -250$ mm. Distances: R1–OC = 380 mm, R2–HR = 430 mm, R1–R2 = 230 mm.

The main difference arises from the fact that the Yb:YLF crystal was uncoated and it was placed at the Brewster angle to minimize reflection losses for the laser polarization, which is oriented along the π -axis of the crystal, corresponding to the extraordinary polarization. The Brewster placement of the active medium permits to compensate the cavity astigmatism due to the non-normal reflection on tilted mirrors R1 and R2 of the X-folded resonator. In our cavity design, given the length and refractive index of Yb:YLF crystal, the exact compensation was obtained by setting the folding angle of the two curved mirrors to $\theta_{\text{opt}} = 6^\circ$ (R1) and 4° (R2) respectively.

However, given the birefringence of the uniaxial YLF crystal and the orthogonal polarization of the two polarization-coupled tapered diodes of our pump module, the Brewster placement of the active medium introduces a secondary effect. The pump beam refraction at the Brewster angle separates the propagation directions of the ordinary (σ)

and extraordinary (π) pump beam. The pump beam component polarized along σ experiences an angular displacement with respect to the π -polarized component, that produces a lateral shift inside the crystal, commonly referred to as *walk-off*. The walk-off angle is given by

$$\rho = |\theta_{\sigma,in} - (\pi/2 - \theta_B)| \quad (4.6)$$

where $\theta_{\sigma,in}$ is the angle of refraction inside the material for the pump beam polarized along the ordinary (σ) direction for an incidence at $\theta_B = \arctan(n_e)$, whereas $\pi/2 - \theta_B$ is the angle of refraction of the pump component polarized along the extraordinary (π) direction, which corresponds also to the propagation direction of the laser beam inside the resonator, if we neglect the dispersion of the extraordinary refractive index of the material for the two, relatively close wavelengths $\lambda_p \simeq 980$ nm and $\lambda_L \simeq 1030$ nm.¹

By simply applying the Snell's law, and given the values of $n_e = 1.47$ and $n_o = 1.45$ for Yb:YLF at 1 μ m, we get:

$$\rho = |\theta_{\sigma,in} - (\pi/2 - \theta_B)| = \left| \arcsin\left(\frac{\sin(\arctan(n_e))}{n_o}\right) - \frac{\pi}{2} + \arctan(n_e) \right| \simeq 9.4 \text{ mrad} \quad (4.7)$$

The lateral displacement of the centroid of the pump beam polarized along the σ direction with respect to the laser beam polarized along the π direction will be simply given by

$$\delta x = \rho L_{eff} \quad (4.8)$$

where L_{eff} is the effective length of the propagation inside the Yb:YLF crystal placed at the Brewster angle. Indeed, the sample we had at our disposal was not Brewster-cut and had a length $L = 5.2$ mm. Because of Brewster orientation, the length of the path of the pump/laser beam inside the crystal is given by:

$$L_{eff} = \frac{L}{\cos(\theta_{in,\pi})} = \frac{L}{\cos\left(\frac{\pi}{2} - \arctan(n_e)\right)} \simeq 6.3 \text{ mm} \quad (4.9)$$

¹For Yb:YLF dispersion of the refractive index between the pump and the laser wavelength accounts for a $\Delta n_e \sim 4 \cdot 10^{-4}$ [62], which is clearly negligible for our purposes!

According to eq. 4.8, this results in a lateral displacement at the end of the active medium $\delta x \simeq 60 \mu\text{m}$, which is already quite significant if compared to the cavity mode beam waist in the horizontal plane, which is expanded by a factor n_e due to the Brewster orientation of the crystal to $\approx 50 \mu\text{m}$ inside the active medium, as it can be seen in the ABCD simulations results presented in Fig. 4.18. This suggests that a shorter crystal (e.g $L = 4 \text{ mm}$) would be better suited for our experimental setup.

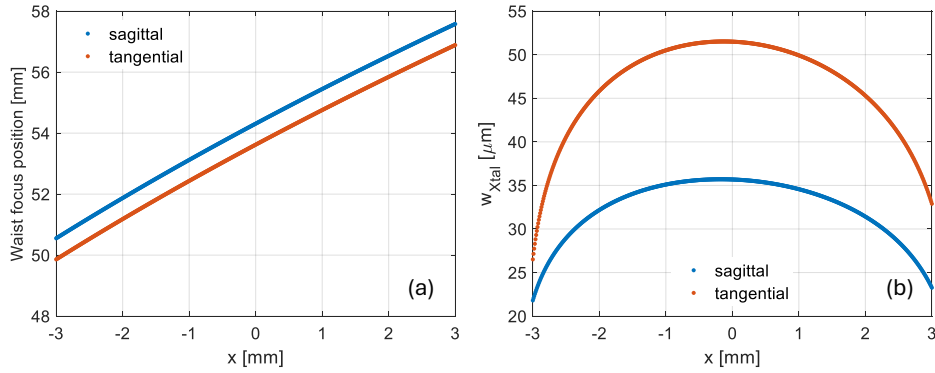


FIGURE 4.18: (a) Beam waist asymmetry inside the uncoated Yb:YLF crystal due to Brewster angle incidence. (b) Waist in the active medium. The abscises axis measures the displacement of mirror R2 from its reference position in Fig. 4.17. A positive value indicates that the mirror is farther from the crystal, while a negative value means it is closer.

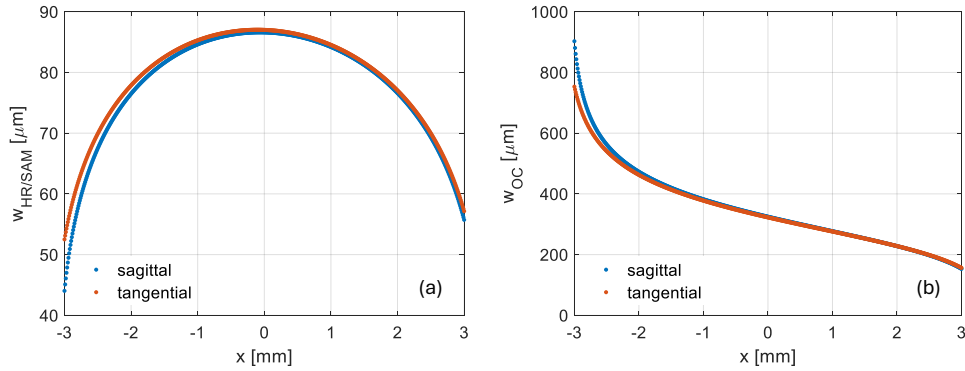


FIGURE 4.19: (a) Beam waist on the HR/SAM mirror(a) and on the OC mirror(b). The abscises axis measures the displacement of mirror R2 from its reference position in Fig. 4.17. A positive value indicates that the mirror is farther from the crystal, while a negative value means it is closer.

An additional effect that should be taken into account is the partial reflection at the

air–crystal interface for s -polarized component of the pump beam due to Fresnel reflection. This effect is obviously absent for the π -polarized component, which is at the Brewster incidence angle. The Fresnel equations permit to easily calculate the reflectivity at the Brewster oriented interface for the σ -polarized component of the pump beam:

$$R_s(\theta_B) = \left| \frac{n_0 \cos \theta_B - n_1 \cos \theta_t}{n_0 \cos \theta_B + n_1 \cos \theta_t} \right|^2 \simeq 12\% \quad (4.10)$$

The laser output power as a function of the absorbed pump power for various OC transmissions is shown in Fig. 4.20. We measured the transmitted pump power behind the dichroic mirror and including twice the additional 12% loss due to the reflectivity of the air–crystal and crystal–air interfaces ($R_s(\theta_B)$). The absorbed pump power was then obtained by simply taking the difference between the incident pump power and the transmitted power.

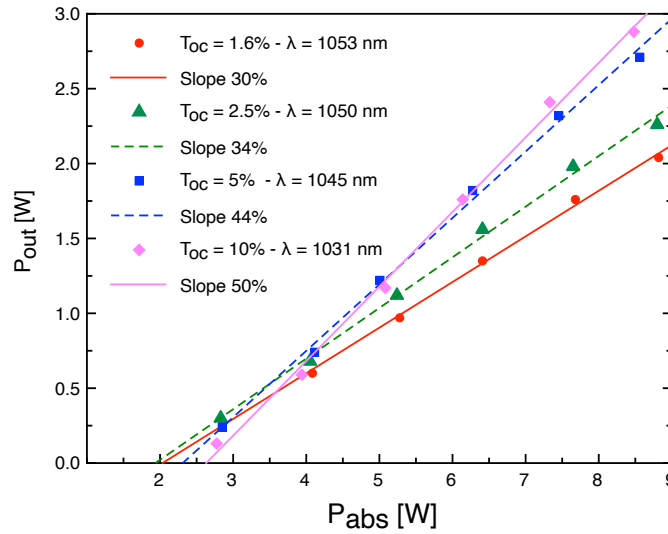


FIGURE 4.20: CW output power vs. absorbed pump power for different output coupler transmissions.

The maximum output power of about 2.8 W was measured with the $T = 10\%$ OC, with a slope efficiency reaching 50%. As expected, increasing the OC transmission raised the total cavity losses and resulted in a blue shift of the lasing wavelength, as typically happens for quasi-three level materials. The output wavelength varied between 1053 nm with a 1.6% OC and 1031 nm with the 10% OC.

Likely due to the high doping-length product, the laser threshold was mainly set by the re-absorption losses. Indeed we measured a threshold pump power of $\simeq 2$ W for $T_{OC} = 2.5\%$, that increased only to 2.6 W for the 10% OC.

The highest slope efficiency was obtained with the 10% OC, nevertheless, even with the lowest OC tested (1.6%), the slope efficiency remained quite high, around 40%.

Considering the additional losses introduced by the SESAM and the need to ensure stable mode-locking, we opted for the 5% OC for the femtosecond mode-locked experiments rather than the 10% OC.

A Caird analysis (Eq. 4.4) estimated an intrinsic efficiency of approximately 60%, which is higher than that obtained with Yb:CaF₂ (see Fig. 4.21). The round-trip losses were estimated to be $\simeq 1.5\%$, which is reasonably low. It should be noted that anti-reflection coatings usually introduce higher losses compared to what can be achieved by carefully aligning the crystal at Brewster angle. In our case, the crystal mounting did not allow for precise adjustment to the exact Brewster angle, and therefore the slightly higher cavity losses observed with Yb:YLF, when compared to Yb:CaF₂, can reasonably be attributed to this imperfect alignment. Since the same cavity mirrors were used in both cases, the only other possible contribution to the increased losses could be the intrinsic quality of the crystal itself, for example scattering losses.

Overall, even with a relatively long active medium, the asymptotic efficiency η_0 , accounting also for spatial overlap between the pump and the cavity mode along the active medium, was good.

4.2.2 Yb:YLF Mode-locking Experiments

After completing the CW characterization, passive mode-locking was implemented by introducing GTIs for dispersion management and replacing the HR mirror with a SESAM as we did for Yb:CaF₂ laser. The optimized cavity layout is shown in Fig. 4.22. Three GTI mirrors provided a total GDD of about -1400 fs².

We also measured the spatial beam, quality of the laser output. As shown in Fig. 4.23, the beam waist was measured to be approximately 36×34 μm^2 , with M^2 values of 1.02

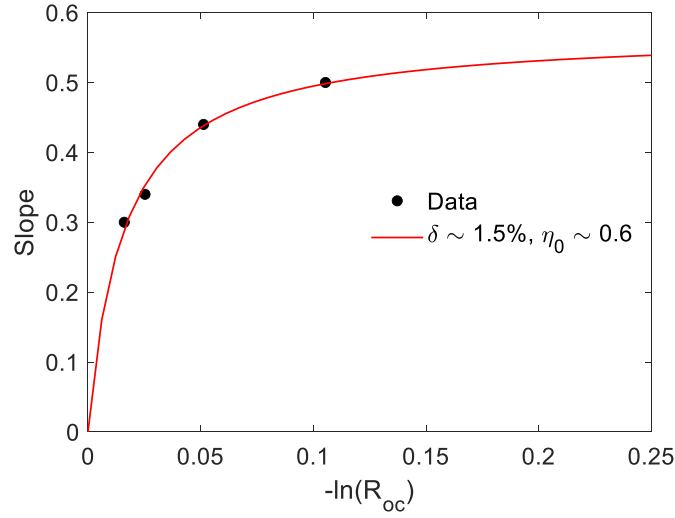


FIGURE 4.21: Caird plot for the Yb:YLF laser: measured slope efficiency vs. output coupling ratio.

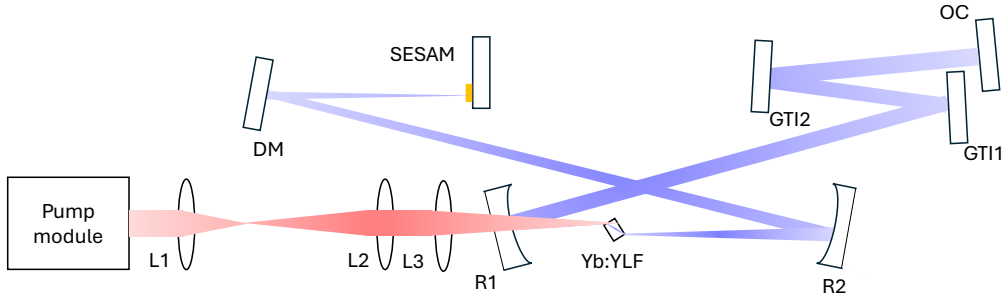


FIGURE 4.22: Schematic layout of the Yb:YLF ML oscillator. DM: dichroic mirrors; OC: wedge output coupler; L1: $f = 30$ mm; L2, L3: $f = 100$ mm; GTI1, GTI2: -350 fs² GDD each; R1: dichroic spherical mirror (HT @ 980 nm, HR @ 1050 nm), $R = -100$ mm; R2: spherical mirror, $R = -250$ mm. Distances: R1–OC = 380 mm, R2–SESAM = 430 mm, R1–R2 = 230 mm.

and 1.03 along the x - and y -axes, respectively. We got an excellent circular beam with diffraction limited beam quality, confirming the benefit of the Brewster-oriented active medium in the X-folded resonator.

We tested both a 5% OC and a 2.5% OC. The best results in terms of spectrum and autocorrelation traces of the ML pulses are shown in Fig. 4.24.

For the 5% OC (Fig. 4.24(a)), we achieved an average output power of 2.2 W with a 14 nm FWHM spectrum centered at 1042 nm, yielding 95 fs pulses. With the 2.5% OC

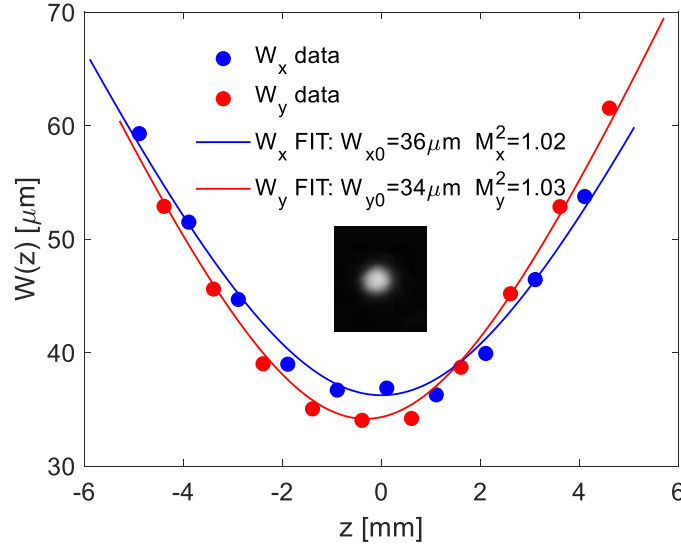


FIGURE 4.23: Measured beam profile and M^2 parameters for the GTI-based setup.

(Fig. 4.24(b)), the output wavelength red-shifted to 1051 nm and the power dropped significantly to 1.3 W. The spectrum broadened to 17.5 nm, with residual CW components that we could not eliminate near 1051 nm. The shortest pulses were 84 fs long, with a TBP = 0.4, close to the Fourier-transform limit for sech^2 pulses. Especially in this latter condition, in which the spectra broaden to about 17 nm FWHM, the ML regime was quite unstable. This, in combination with the presence of the cw components in the spectra, suggests that laser intracavity GDD compensation was not optimized. In future experiments, we intend to change the layout of the resonator by exploiting the 1st stability region and by exploring an optimal cavity GDD compensation with a pair of FS prisms. An additional improvement may arise from a better selection of the crystal length. New, slightly shorter (3.5-4 mm-long) Yb:YLF and Yb:LLF samples have been ordered and will be tested in the near future.

Table 4.1 summarizes the main performance of Yb:YLF lasers operating below 100 fs reported in the literature, together with the results obtained in this work. The comparison clearly highlights a substantial improvement in both average and peak powers achieved in similar pumping conditions.

Previous studies, such as [41] and [42], demonstrated sub-100 fs pulse generation but

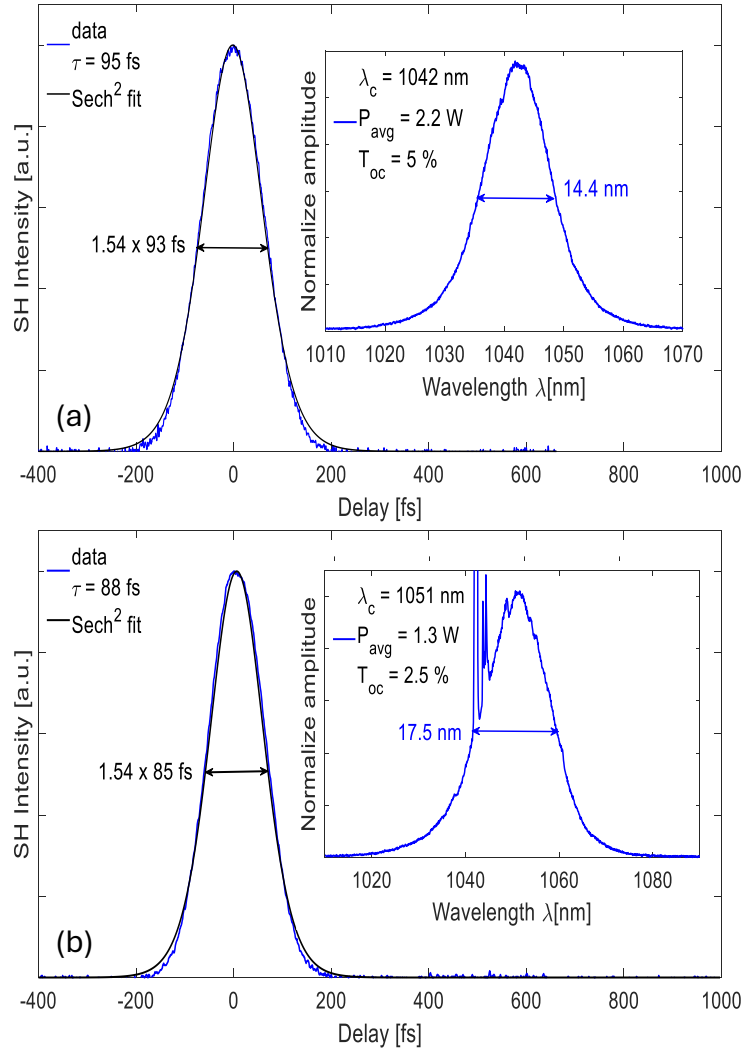


FIGURE 4.24: (a) ML spectrum with 5% OC. (b) More stable output with 2.5% OC. (c) Near-unstable regime showing the broadest spectrum.

TABLE 4.1: Yb:YLF laser below 100 fs in literature

Ref.	P_{pump}	Pump diode	P_{avg}	E_p	τ_p	P_{peak}
[41]	600 mW	Fiber coupled single mode	35 mW	350 pJ	87 fs	4 kW
[42]	10 W	Multimode	265 mW	3 nJ	40 fs	75 kW
[42]	10 W	Multimode	1.85 W	10 nJ	380 fs	26 kW
This work	10 W	High brightness TD	2.2 W	16 nJ	93 fs	170 kW

with limited output power, typically ranging from a few tens to a few hundreds of mW and an optical-to-optical efficiency of few percent (about 6% in [41] and < 3% in [42]).

In [41], 87 fs pulses were obtained with an average power of 35 mW pumping with two fiber-coupled single-mode diodes at 976 nm providing a maximum incident power of 600 mW, while [42] reported 40 fs pulses with 265 mW average power pumping with a multimode 10 W laser diode at 960 nm. In the same work, a higher average power of 1.85 W was achieved, but at an expense of a significantly longer pulse duration of 380 fs, corresponding to a peak power of approximately 26 kW.

In contrast, the laser developed in this work delivers 2.2 W of average power with 93 fs pulse duration and 16 nJ pulse energy, resulting in a peak power of nearly 170 kW and an optical-to-optical efficiency of 22%. This represents a remarkable enhancement in both pulse efficiency, pulse peak power and energy scaling compared to previous Yb:YLF systems operated under comparable 10 W pumping conditions with pulses below 100 fs.

These results confirm the excellent potential of the tapered diode pump unit and Yb:YLF for generating high-energy, sub-100 fs pulses with outstanding spatial and temporal quality. We are confident that, with the new Yb:YLF sample with optimized crystal length and with a better management of intracavity GDD, it will be possible to further shorten the pulse duration significantly, setting an even higher benchmark for Yb:YLF laser performance in this regime.

Conclusions

In conclusion, the research activity carried out in this PhD thesis has demonstrated that high-brightness tapered diode lasers are highly effective pump sources for both femtosecond amplifiers and oscillators based on Yb-doped materials. The experiments confirmed that the combination of high optical power and near-diffraction-limited beam quality enables efficient pumping of quasi-three-level materials, which typically require high pump intensities to achieve population inversion.

In the amplification studies, a high double-pass small-signal gain of $G_0 \approx 40$ and an optical-to-optical efficiency of 50% were demonstrated using a single-diode, single-crystal setup. The most advanced configuration, consisting of two crossed Yb:KYW crystals (3 mm each) pumped by a dual-diode module delivering up to 10 W, allowed amplification of a 20 mW seed to 2 W of output power, corresponding to a total gain of $G = 100$. Remarkably, no amplified spontaneous emission (ASE) was observed even with a very high four-pass small-signal gain of $G_0 \approx 500$. The amplified pulses maintained durations below 200 fs, exhibiting negligible temporal distortion and excellent spatial quality ($M^2 < 1.1$). These results demonstrate that tapered-diode pumping can provide strong gain and efficient energy extraction in compact amplifier architectures, with stable operation and limited thermal effects. It is expected that future implementations of the crossed-crystal amplifier, featuring improved thermal contact and active cooling of the gain media, will further increase the achievable G_0 and overall system efficiency.

The second part of this thesis focused on the development of diode-pumped femtosecond oscillators, confirming the excellent performance of the Yb:YLF system, which

generated 93 fs pulses with an average output power of 2.2 W. In continuous-wave operation, further performance improvements were achieved by increasing the output coupling ratio, reaching nearly 3 W with a 10% output coupler transmission. A Caird analysis confirmed the very low intracavity losses and an asymptotic efficiency of approximately 60%. These results further demonstrate that tapered-diode pumping can directly sustain high-power, high-quality continuous-wave and mode-locked operation without the need for intermediate amplification stages. Future experiments will employ shorter (3.5 mm) Yb:YLF crystals, which are expected to improve mode-locking stability, optimize dispersion management, and enable the generation of even shorter pulses. Overall, this research confirms the potential of high-brightness tapered diodes to serve as efficient and compact pump sources for ultrafast Yb-based solid-state lasers. The combination of high gain, stable operation, and excellent spatial quality establishes a foundation for further optimization and scaling.

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