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FEMTOSECOND INDUSTRIAL LASERS

Candidate: Matteo Miccoli

Supervisor: Prof. Antonangelo Agnesi

Co-supervisor: Prof. Riccardo Gotti

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SOMMARIO

Questo lavoro di Tesi presenta la progettazione e la validazione sperimentale di sorgenti laser in fibra ottica drogata con Itterbio (Yb) per la generazione di impulsi ultracorti nei femtosecondi a 1030 nm. L'attività risponde alla richiesta industriale di architetture laser compatte, stabili e ad alta energia, superando i limiti di sensibilità ambientale dei sistemi a stato solido bulk.

Nella prima parte dell'elaborato, viene analizzato un oscillatore a solitone dissipativo in regime di dispersione normale (All-Normal Dispersion, ANDi), che utilizza uno specchio assorbitore saturabile a semiconduttore (Semiconductor Saturable Absorber Mirror, SESAM) per il mode-locking in self-starting. Vengono confrontate una configurazione ad anello ed una lineare; quest'ultima è stata selezionata per ovviare alle instabilità di ampiezza e alle perdite intracavità riscontrate nella cavità ad anello. La configurazione lineare ottimizzata ha generato impulsi stabili con bande di circa 8 nm centrati a 1030 nm, potenza media di 30 mW a una frequenza di ripetizione di 25 MHz e durate dell'impulso non compresso di 10 ps. Vengono inoltre presentati i test di amplificazione non lineare in fibra in regime 'gain-managed' (Gain-Managed Nonlinear Amplification, GMNA). Pre-comprimendo gli impulsi, il sistema ha generato spettri amplificati superiori a 65 nm, comprimibili a circa 40 fs con potenze medie di 3 W a 25 MHz.

Nella seconda parte, per superare i limiti di degradazione termica del SESAM, lo sviluppo si è concentrato su un prototipo industriale di oscillatore Mamyshev. Sfruttando l'auto-modulazione di fase (SPM) e il filtraggio spettrale disassato tramite due filtri passa-banda non sovrapposti, l'architettura realizza un assorbitore saturabile virtuale ad altissima dinamica che sopprime l'emissione in onda continua (Continuous-Wave, CW). Il prototipo, ottimizzato e ingegnerizzato presso le strutture aziendali in collaborazione con il Laboratorio Sorgenti Laser (LSL) dell'Università di Pavia, ha generato treni d'impulsi stabili a 10.44 MHz, con larghezze spettrali di circa 20 nm, impulsi non compressi di pochi picosecondi e potenza media di 50 mW. I modelli numerici e i parametri di riferimento precedenti indicano che si prevede che il successivo GMNA di questa sorgente di seed produrrà spettri larghi oltre 100 nm, comprimibili a 30 fs con potenze medie di circa 2 W, validando la robustezza del front-end per applicazioni industriali.

ABSTRACT

This Thesis presents the design and experimental characterization of Ytterbium (Yb) doped fiber laser sources delivering ultrashort femtosecond pulses at 1030 nm, addressing the industrial demand for compact, stable, and high-energy laser architectures.

The first part of this work investigates a dissipative soliton oscillator operating in the All-Normal Dispersion (ANDi) regime, utilizing a Semiconductor Saturable Absorber Mirror (SESAM) to achieve self-starting mode-locking. A linear cavity configuration was selected over a preliminary ring design to mitigate pulse train amplitude fluctuations and intracavity insertion losses. The optimized linear oscillator delivered stable pulses with an 8 nm bandwidth centered at 1030 nm, yielding an average output power of 30 mW at a 25 MHz repetition rate and an uncompressed pulse duration of approximately 10 ps. These pulses were subsequently used to seed a Gain-Managed Nonlinear Amplification (GMNA) fiber stage. By implementing external pulse compression prior to amplification, the setup achieved amplified spectra wider than 65 nm, compressible down to 40 fs, with an average output power of 3 W at 25 MHz.

The second part of the Thesis describes the development of an industrial-grade Mamyshev oscillator designed to bypass the physical and thermal damage thresholds of SESAMs. By combining self-phase modulation (SPM) in the fiber with two non-overlapping bandpass filters, the cavity implements a high-modulation-depth virtual saturable absorber that completely suppresses continuous-wave (CW) oscillation. The prototype, engineered in cleanroom facilities in collaboration with the Laser Sources Laboratory (LSL) of the University of Pavia, delivered stable mode-locked pulse trains at a repetition rate of 10.44 MHz, with a spectral bandwidth of approximately 20 nm, uncompressed pulse durations of a few picoseconds, and an average power of 50 mW. Numerical models and previous benchmarks indicate that subsequent GMNA of this seed source is projected to yield spectrally broadened pulses exceeding 100 nm, compressible to 30 fs with an average power of 2 W, demonstrating a highly robust platform for industrial applications.

INTRODUCTION

I.1 Ultrafast lasers architectures: bulk and fiber lasers

Optical sources engineered to generate pulses with durations ranging from several picoseconds down to a few femtoseconds define the domain of ultrafast lasers. Through advanced techniques such as high-harmonic generation, these operational boundaries can be extended into the attosecond regime. Over the past few decades, both the scientific community and industrial sectors have shown a growing interest in the physics underlying these systems, driven by their profound implications across multiple disciplines. This attention is due to the very high peak powers that these sources can deliver, a direct consequence of their extreme temporal compression [1]. The practical implementations of these architectures span numerous fields. In biophotonics, they function as indispensable excitation sources for techniques like two-photon microscopy and optical coherence tomography (OCT), allowing for detailed, non-invasive imaging of living tissues. Clinical medicine heavily relies on these lasers for high-precision dermatological therapies and advanced eye surgeries. From a fundamental physics perspective, these intense optical fields allow researchers to probe the primary properties of matter and drive frontier developments like laser-induced nuclear reactions, while also expanding the capabilities of infrared spectroscopy for evaluating complex molecular dynamics and structural compositions.

Introducing Kerr-lens mode-locked Titanium-Sapphire (Ti:Sa) solid-state oscillators, these devices entered the market in the late 1980s and became the gold standard for ultrafast performance. These systems generate pulses in the tens of femtoseconds range commercially and can reach few-cycle durations in research laboratory environments. Operating in the solitonic regime [2], Ti:Sa lasers naturally output high-quality, pedestal-free pulses that are nearly Fourier-transform limited, exhibiting near-ideal spectral profiles. However, the commercial limitation of traditional ultrafast lasers is the disproportionate cost [3], because Ti:Sa demands excitation within the green spectral band, it relies on expensive, bulky frequency-doubled solid-state pump lasers. For example, a green pump laser for a Ti:Sapphire costs tens of thousands of euros, has a limited useful life and consumes a lot of current and water for cooling. This changed significantly with the implementation of SESAMs for passive mode-locking at 1 μm [4], alongside the commercialization of high-brightness, high-power InGaAs laser diodes operating between 940 nm and 980 nm. This synergy has driven intensive materials research, resulting in a rapid expansion of high-performance femtosecond bulk systems based on Ytterbium-doped crystals. These Yb-doped solid-state sources currently represent the state of the art for industrial applications, challenging the historical monopoly of Ti:Sa even in regimes requiring sub-100 fs pulse durations.

Despite these remarkable achievements, femtosecond solid-state bulk architectures possess intrinsic structural limitations. While it is possible to directly extract extremely high pulse energies (up to 1–10 μJ) and significant average powers (10–100 W) from bulk oscillators—particularly by employing highly complex thin-disk geometries [5]—scaling the pulse energy inherently requires lowering the pulse repetition rate (PRR). Because the PRR in a mode-locked cavity is inversely proportional to the resonator length [1], accommodating lower repetition rates demands the design of very long free-space cavities.

Such extended resonators are inevitably bulky and highly susceptible to environmental disturbances due to their significant misalignment sensitivity.

To bypass these limitations, the subfield of ultrafast fiber lasers has experienced rapid growth in recent years, intensified by continuous advancements in fiber technology. Fiber-based architectures introduce decisive advantages over their solid-state counterparts. They offer intrinsic compactness and robustness, exceptional light confinement due to the waveguiding effect, high spatial beam quality, and an alignment-free optical layout. Additionally, the geometry of optical fibers allows for highly efficient heat dissipation, making them perfectly suited for high average power applications. Coupled with the improvements in pump diode performance, fiber lasers have become highly efficient and increasingly competitive from a pricing perspective [6].

All ultrafast fiber lasers rely on passive mode-locking mechanisms to generate ultrashort pulses [7]. This process requires a saturable absorber to trigger pulse formation within the cavity. From the initial noise and random intensity fluctuations, the saturable absorber selectively amplifies the highest intensity peaks, allowing these fluctuations to gradually evolve into short pulses. Over the past three decades, various saturable absorption devices have been developed; among them, the SESAMs are the most commonly employed for passive mode-locking. However, the main drawback of these devices is their susceptibility to optical damage. In free-space bulk lasers, this issue can be managed to some extent by adjusting the cavity mode radius to control the intensity and fluence incident on the SESAM. Unfortunately, in a fiber laser, the mode dimension is strictly fixed to guarantee fundamental single-mode propagation. This tight spatial confinement leads to intense power densities that can easily approach, or even exceed, the optical damage threshold of the SESAMs [8]. As an alternative to material-based absorbers, artificial saturable absorption mechanisms exploiting nonlinear effects taking place within the fiber itself can be utilized to produce a saturable-absorber-like behaviour.

When compared to their solid-state counterparts, ultrafast fiber lasers are subjected to significantly stronger dispersive and nonlinear effects. This is directly attributed to the tight confinement of light within the fiber core, which generates extremely high-power densities circulating inside the cavity. As a result, any attempt to achieve higher pulse energies and shorter pulse durations invariably increases the peak power, which concurrently leads to a high degree of nonlinearity. The primary physical phenomenon that bottlenecks the achievable peak powers in these fiber lasers is Self-Phase Modulation (SPM) [9].

Most ultrafast fiber laser designs originally aimed to mitigate these nonlinear effects by keeping the nonlinear phase shift at a minimal level. However, the most significant improvements in the overall performance of ultrafast fiber lasers, particularly concerning the crucial challenge of pulse energy scaling, have been directly linked to advancements in our understanding and possibility to actively manage and exploit nonlinear pulse evolution to our advantage [10]. The progressive leaps in achievable peak power demonstrated over the last decades are the direct result of new, highly nonlinear fiber oscillator architectures that have been proposed and refined. During the historical evolution of fiber laser architectures, each architecture represents a distinct physical method for pulse shaping and nonlinear phase management. The fundamental operating regimes of ultrafast fiber oscillators are classified as follows:

- **Soliton mode-locking:** Operating in the anomalous dispersion regime, solitons arise from a conservative balance between the fiber's negative group velocity dispersion (GVD) and the positive chirp induced by SPM. This allows the pulse to propagate without temporal

or spectral distortion, yielding clean, near-transform-limited profiles. However, soliton operation faces severe limitations regarding energy scalability. Bounded by the soliton area theorem, any attempt to increase the pulse energy beyond a specific threshold (typically in the sub-nanojoule range) triggers intense nonlinear instabilities and wave-breaking. Consequently, conventional fiber solitons are largely restricted to low-energy, picosecond-domain applications [7].

- **Dispersion-managed soliton:** To overcome the strict energy limitations of the pure solitonic regime, Dispersion-Managed (DM) cavities are engineered with alternating segments of positive and negative GVD. This forces the pulse to undergo massive temporal expansion and compression during each roundtrip. By increasing the average pulse duration inside the active medium, the intracavity peak power is significantly reduced, mitigating excessive SPM accumulation. This controlled nonlinear management allows DM oscillators to sustain higher energies, scaling the extractable peak power into the tens of kilowatts range [11],[12].

- **Self-similar regime:** Pulses evolving in normally dispersive resonators can develop a parabolic temporal intensity profile paired with a linear up-chirp. Under the combined influence of normal GVD and SPM, the pulse continuously broadens in both the temporal and spectral domains while maintaining its shape as a scaled replica of itself (similariton). While these pulses offer excellent external compressibility, the ultimate energy scaling of self-similar oscillators is blocked by the finite gain bandwidth of the active medium and the unavoidable onset of stimulated Raman scattering at higher intensities [3].

- **Dissipative Soliton:** Operating entirely within the All-Normal Dispersion regime, dissipative solitons rely on a complex, non-conservative balance. The strong temporal and spectral broadening induced by normal GVD and SPM is actively counteracted by a narrow spectral filter, which reduces the nonlinear spectral wings and enforces pulse shortening. As detailed in the experimental core of this Thesis, the DS architecture was initially selected and extensively investigated due to its simplified cavity layout and reliable self-starting capabilities, typically mediated by a SESAM. However, there are structural limitations: beyond a certain pump power we can incur multi-pulse instabilities, pulse breakdown and an unacceptable risk of optical damage to the physical absorber [13].

- **Mamyshev Oscillator:** Originally conceived as an all-optical regenerator for telecommunications [14] and later adapted for mode-locking [15], this cavity concept employs offset spectral filtering. A pulse propagating in the nonlinear fiber experiences massive SPM-driven spectral broadening, allowing a portion of its newly generated spectrum to pass through a subsequent band-pass filter shifted from the original central frequency. By cascading two non-overlapping filters, continuous-wave (CW) is entirely suppressed. Only pulses with sufficient peak power to bridge the frequency gap via SPM can circulate, creating a virtual saturable absorber with an unparalleled, almost infinite modulation depth [10], [15]. Given its exceptional environmental reliability and its capacity to directly deliver microjoule-level energies and megawatt peak powers without degradable physical absorbers [13], the Mamyshev configuration was identified as the ideal platform for the industrial prototype. This choice was further motivated by the extensive theoretical and experimental studying developed on this specific architecture by the Laser Sources Laboratory at the University of Pavia.

I.2 DS ANDi Oscillators

The Dissipative Soliton (DS) oscillator operating in an ANDi regime represents a highly effective architecture for generating ultrashort pulses without relying on anomalous dispersion components. The fundamental innovation of the ANDi regime lies in its non-conservative pulse shaping mechanism. Unlike conventional solitons, where the pulse phase is preserved through a perfect balance between GVD and SPM, a dissipative soliton is formed through a complex interplay involving normal GVD, intense SPM, linear gain, and, crucially, localized spectral filtering. In the presence of a normally dispersive nonlinear medium, an intense pulse accumulates a strong, highly linear frequency chirp. The leading edge of the pulse shifts toward lower frequencies (red-shifted), while the other edge shifts toward higher frequencies (blue-shifted). Simultaneously, significant spectral broadening via SPM generates new frequency components and if left unchecked, the pulse would continuously broaden both spectrally and temporally, eventually leading to the breakdown of the mode-locked state. To counter this, a narrow band-pass spectral filter is introduced into the cavity. This filter systematically cuts off the highly chirped temporal wings of the pulse, effectively shortening it in the time domain at each roundtrip. The combination of nonlinear broadening and linear filtering ensures that the pulse converges to a stable, steady-state solution, typically characterized by a cat-ear-shaped optical spectrum.

The standard layout for a DS oscillator operating in ANDi regime has the cavity composed entirely of normal-dispersion fibers, primarily an active Ytterbium-doped fiber providing the gain and lengths of passive fiber accumulating the required nonlinear phase shift. The self-starting mechanism of the oscillator is provided by a SESAM. Examining the pulse evolution through the cavity: the pulse is amplified in the active medium, experiencing simultaneous normal dispersion and SPM. As its peak power grows, the spectral bandwidth rapidly expands. Upon reaching the spectral filter, the newly generated outermost frequency components are eliminated. The filtered, temporally shortened pulse then interacts with the SESAM, which discriminates against low-intensity CW background noise, reinforcing the high-peak-power pulsed operation before the cycle repeats.

I.3 Amplification strategies for DS ANDi and MO oscillators: CPA and GMNA

As discussed in the previous sections, scaling the circulating pulse energy within a fiber oscillator eventually triggers nonlinear instabilities. Specifically, both the DS ANDi and the Mamyshev oscillator (MO) are fundamentally constrained by the same physical limitation: pulse splitting. As observed by Regelskis [16], when the intracavity energy exceeds a critical threshold, the single pulse breaks down and the cavity transitions into a harmonic mode-locking regime, characterized by multiple temporally equally spaced pulses. While both architectures share this limitation, the intrinsic robustness of the Mamyshev mode-locking mechanism actually enables the MO to tolerate greater nonlinear phase shifts, allowing it to sustain slightly higher pulse energies compared to its ANDi counterpart.

To achieve a significant energy scaling beyond this splitting threshold, two primary approaches exist. The first relies on high-power oscillators pumped by multimode diodes at approximately 10 W. Thanks to its highly stable mode-locking dynamics, the MO can be pushed in this configuration to deliver energies up to the microjoule (μJ) level directly from the oscillator. The second approach is Chirped Pulse Amplification (CPA), which provides even higher energies and maximum operational flexibility, allowing a system to be tailored either for high-energy pulses at low repetition rates or for high average power at lower pulse energies.

Although a high-power MO can directly generate μJ -level pulses, practical experimental experience reveals a critical reliability issue. High-power, high-gain oscillators necessitate the use of double-clad (DC) fibers, making them significantly more susceptible to irreversible optical damage compared to standard single-mode (SM) oscillators pumped by low-power diodes in the few-hundred-milliwatt range. Consequently, to ensure long-term reliability without sacrificing output performance, a highly robust alternative to the high-power MO is the Master Oscillator Power Amplifier (MOPA) architecture, specifically pairing a low-power SM Mamyshev seed oscillator with a GMNA stage. To address the issue of pulse energy scalability, various amplification solutions have been explored. The most prominent pulse amplification techniques are evaluated below:

- **CPA:** Chirped Pulse Amplification is a standard, highly effective technique that allows the amplification of ultrashort pulses to extreme peak-powers without risking the potential optical damage that such high intensities could inflict on the fiber components. The fundamental principle of CPA involves a source of ultrashort pulses that serves as the seed for amplification. Initially, the pulse passes through a dispersive pulse stretcher, which introduces massive group velocity dispersion (GVD) to stretch the pulse in the time domain. Subsequently, the pulse is amplified and then recompressed using a grating pair. While the incorporation of large-mode-area (LMA) fibers has greatly improved the effectiveness of fiber-based CPA, this architecture presents some fundamental drawbacks. Primarily, the compressed pulses in standard fiber CPA rarely reach durations below 200 fs, being limited by the gain narrowing of the active

medium and the residual third-order dispersion mismatch between the stretcher and compressor stages [8].

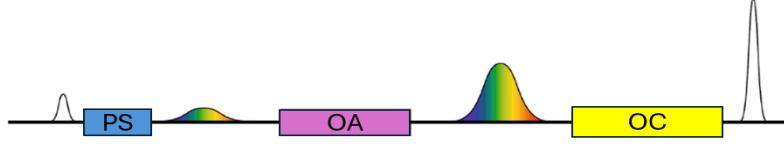


Figure 1.1 Scheme of a CPA, PS: Pulse stretcher. OA: Optical amplifier. OC: Optical compressor.

- GMNA:** Gain-Managed Nonlinear Amplification represents a more recent and highly innovative paradigm for pulse energy scaling, first conceptualized and demonstrated around 2019 [17]. Unlike traditional CPA, which actively avoids nonlinearities, GMNA intentionally exploits the nonlinear SPM interacting with the dynamically evolving gain spectrum of the Ytterbium-doped fiber. If a moderately chirped, relatively short pulse, such as the one directly delivered by a DS ANDi or MO oscillator, is injected into the active fiber, it rapidly accumulates SPM. However, around 1020 nm, the pulse encounters the strong absorption edge of the unpumped or partially inverted Ytterbium sections. Because this short-wavelength edge is clamped by absorption, the spectrum cannot broaden symmetrically. Instead, the interplay between SPM and the actively managed gain forces the spectrum to broaden asymmetrically toward longer wavelengths, surpassing the standard 30 nm gain bandwidth of Ytterbium (centered around 1030 nm). This process yields extremely broad, flat-topped spectra (when viewed in logarithmic scale) that can span from 1000 nm up to 1100 nm. This is a remarkably advantageous regime: by bypassing the need for a complex external stretching stage, the pulse can be amplified directly from the oscillator and subsequently compressed down to sub-50 fs durations with exceptional quality. Despite its exceptional spectral scaling capabilities, the GMNA regime presents its own physical limitations. As the energy increases and the spectrum broadens toward longer wavelengths, the bottleneck is represented by the onset of Stimulated Raman Scattering (SRS). When the spectrum approaches the 1200 nm region, SRS rapidly transfers energy to incoherent Raman Stokes components, fundamentally degrading the temporal coherence and compressibility of the pulse [17]. To push this limitation further and scale the output energy in a GMNA configuration, it is mandatory to reduce the power density inside the active medium by scaling the fiber core diameter. As will be detailed in the experimental sections of this work, my laboratory activities initially employed a standard 10 μm core Large Mode Area (LMA) fiber to demonstrate the GMNA dynamics. To overcome the SRS threshold and support higher microjoule-level

energies, future upgrades of the system are planned to transition toward larger 20 μm core LMA fibers.

This brief summary of pulse amplification techniques highlights the strategic importance of the oscillator design. It is important to remark that the low-power ANDi DS laser developed in the initial phase of this Thesis is, in principle, an ideal seeder for a MOPA system exploiting the GMNA regime, bypassing the complexities of a traditional CPA setup.

CHAPTER 1

This Chapter presents the design, implementation, and experimental characterization of DS ANDi oscillators. Initially, within the scope of this Master Thesis, has been selected the DS architecture implemented in a unidirectional ring topology as the primary candidate for the ultrafast source. This choice was strongly motivated by the inherently simple nature of the all-fiber design and its reliable self-starting capabilities granted by the SESAM.

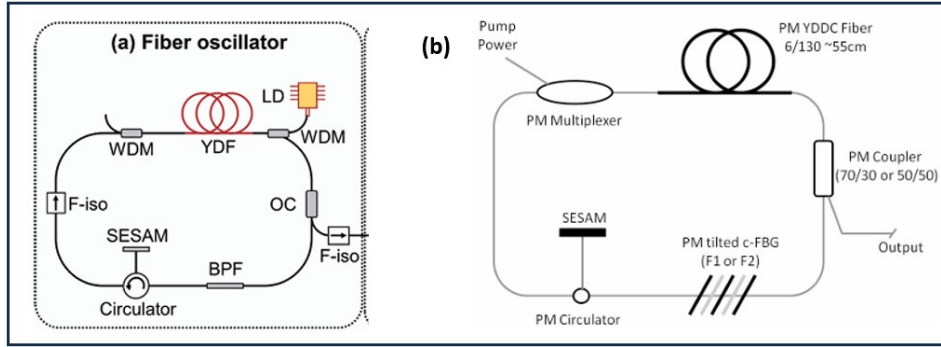


Figure 1.2 (a)(b) Schematic representation of the all-PM unidirectional ring cavities mode-locked by SESAM, utilized as the foundational reference layout [18][19].

The architecture of the low-power ANDi dissipative soliton oscillator investigated initially is linked to the all-PM fiber layouts described in literature, such as those implemented by Kim et al. [18] and Lecourt et al. [19], which is schematically represented in Fig. 1.2. In our specific experimental setup, however, bulk diffraction gratings, fiber Bragg gratings (FBGs), or exotic spectral-shaping items, such as the tilted chirped fiber Bragg gratings utilized by Lecourt et al. [19], were intentionally omitted. Instead, the primary research interest was strictly focused on exploiting the nonlinear amplitude modulation of a SESAM within a unidirectional ring cavity configuration to achieve reliable self-starting passive mode-locking, along with a bandpass dielectric filter for DS shaping and stabilization. For example, the Figure 1.2 (a) design employs a highly doped Ytterbium (Yb) polarization-maintaining (PM) single-mode (SM) fiber as the active gain medium. The active fiber is optically pumped using a fused fiber wavelength-division multiplexer (WDM1), with the pump sourced from a single-mode, fiber-coupled laser diode (Pump LD) emitting at a stabilized central wavelength of 976 nm. The residual pump light that is not absorbed during the single pass through the active fiber is removed from the cavity through a second signal-pump multiplexer (WDM2) to protect subsequent passive inline components from thermal degradation. Unidirectional propagation within the ring loop is enforced by an inline PM optical isolator, which also suppresses parasitic spatial hole burning effects. Additionally, the cavity is monitored via a fused fiber optical coupler (98/02), allowing for the real-time observation of the radiation circulating within the fiber loop. The 2% sample probe from this coupler is continuously employed to assess and optimize the spectral and temporal evolution of the circulating dissipative soliton, while the remaining 98% port recirculates the power back into the cavity. In conclusion, the loop is closed and optical

feedback to the SESAM is provided via a fiber optical circulator, which directs the circulating pulse onto the active semiconductor surface and safely routes the reflected mode-locked pulse back into the fiber loop, completely avoiding free-space components to maximize alignment-free environmental stability. This simplified ring configuration is fundamentally advantageous for the operational lifespan of the optical components: by forcing a single-pass propagation per roundtrip, it significantly reduces the thermal and peak power stress on the intra-cavity elements compared to a standing-wave linear design, theoretically enhancing the long-term reliability of the system. Furthermore, the performance metrics reported in literature for this topology were highly compelling. Operating at a central wavelength of 1030 nm and a repetition rate of ~ 24 MHz, the oscillator delivered a highly stable, chirped dissipative soliton seed that, following subsequent amplification stages, demonstrated compressibility down to 40 fs. These characteristics are exceptionally suitable for acting as a robust front-end seed for fiber amplifiers. Consequently, to exploit its inherent component safety and promising output metrics, reproducing this ring-cavity design appeared to be the most logical and strategic starting point for the experimental activity.

1.1 First ring oscillator layout and preliminary characterizations

The initial experimental phase of this Thesis is focused on the implementation of a unidirectional ring cavity for the ANDi dissipative soliton oscillator. Inspired by recent literature [18, 19], this specific topology was selected for its minimal component count and its single-pass propagation per roundtrip.

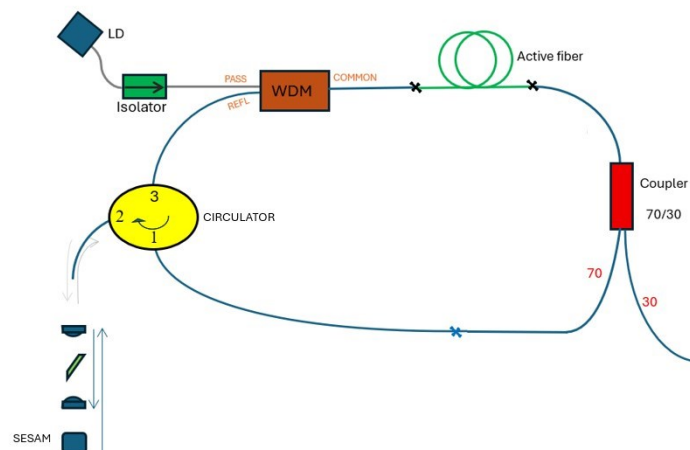


Figure 1.3 Layout of the first ring cavity.

The setup is shown on Fig. 1.3. The primary objective was to achieve a stable, high-repetition-rate oscillator suitable as a robust front-end seed for subsequent amplification. Firstly, a rigorous preliminary characterization of the active pumping section was conducted.

The output power of the 976 nm fiber-coupled pump LD (S/N: AA250924509283) was measured as a function of the driving current to determine its slope efficiency.

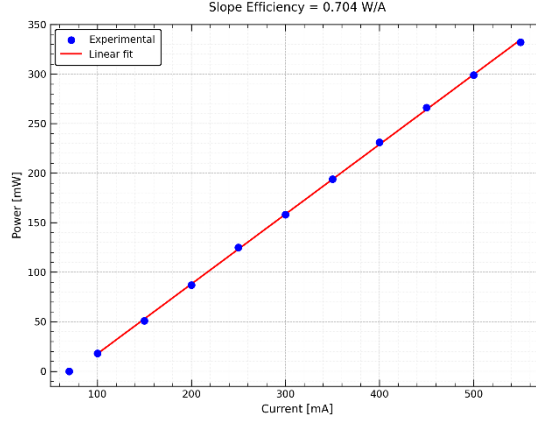


Figure 1.4 Experimental P-I Characteristic curve and Slope Efficiency of the 976 nm pump diode (S/N: AA250924509283).

Fig. 1.4 illustrates the measured LD output power as a function of the driving current. The qualitative behavior of the output power is typical of this class of devices, with a threshold of the laser emission about 75-100 mA of injected pump current, and with an almost linear growth with a slope of ~ 0.7 mW/mA for values of the driving current above threshold. In order to prevent possible damage of the laser diode due to unwanted radiation coming from the resonator towards the pump diode, it was decided to place a Faraday isolator (FI) between the LD and the PM WDM. The transmission spectra and insertion losses of the WDM (P/N: PFWDM-980/1064P9BB10FA, S/N: 23098324) were measured and verified, yielding an optimal transmission of 89% as per datasheet specifications. A relatively short segment (approximately 60 cm) of highly doped Ytterbium (Yb 6/125) PM fiber was selected as the active gain medium. This reduced length was critical to ensure a short total cavity length, enabling a fundamental pulse repetition rate exceeding 20 MHz, which allows maximum flexibility of a fiber amplifier, with either multiwatt output at full repetition rate, or easy pulse-picking for high-energy amplifier output. To balance the cavity output coupling and the intracavity circulating power, multiple fused fiber couplers were integrated and tested during the experimental campaign. While the initial setup employed a 70/30 PM coupler (P/N: PMFIC103012F30B10FA, S/N:23098575), extensive testing was also conducted by substituting it with 30/70 and 50/50 coupling ratios to observe the impact on mode-locking stability and the onset of pulse splitting. Ultimately, a 70/30 splitting ratio (70% intracavity feedback and 30% output coupling) was selected to maximize the balance between intracavity pulse energy and output extraction. To evaluate the mode-locking threshold and ensure the SESAM would not undergo catastrophic optical damage under the circulating intracavity power, the first ring cavity was constructed utilizing a “SESAM-in-air” hybrid coupling approach. The intracavity beam was collimated into free space and focused onto the SESAM using a 1:1 optical telescope. Initially, achromatic lenses with a focal length of 30 mm were employed. In the free-space between the lenses, a tilted bandpass filter (Thorlabs FLH1064-10, 10 nm bandwidth centered at roughly 1030 nm) was inserted. This setup allowed for continuous angle-tuning of the central wavelength without relying on complex, fixed in-fiber tilted FBG as in [19]. While this arrangement successfully initiated passive mode-locking and confirmed that the SESAM could withstand the power without burning, the long focal length rendered the

system extremely susceptible to mechanical fluctuations and highly sensitive to the exact focal position on the translation stage. To mitigate spherical aberrations and defocusing issues, the telescope was subsequently upgraded using short-focal-length aspheric lenses ($f \approx 4.5$ mm). Despite a significant reduction in spherical aberration and a more stable spot size on the SESAM, the extreme sensitivity to the focal plane positioning persisted, leading to unacceptable long-term instabilities.

Figure 1.5 (a) Scheme of the ring cavity all-in fiber setup. (b) Oscillator spectrum with 400 mA of driving current.

power stress on the SESAM and making mode-locking more susceptible to perturbations arising from scattering at the gain grating. However, previous experimental and theoretical fluence validations conducted on the ring configuration ensured that the components could safely support this architectural shift.

1.2 Linear oscillator

Following the instabilities encountered in the unidirectional ring topology, the experimental focus shifted toward this standing-wave linear architecture:

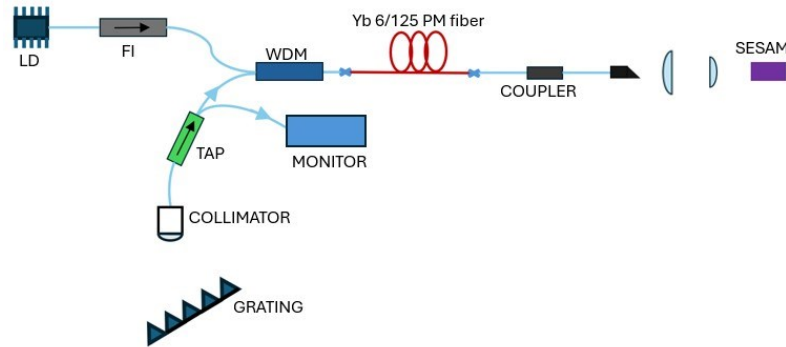


Figure 1.6 Scheme of the first linear cavity with the “SESAM-in-air” setup. LD: Laser Diode. FI: Optical Faraday isolator. TAP: Tap coupler. The free-space section includes a fiber collimator and short-focal-length aspheric lenses to focus the beam onto the physical absorber. Passive PM fibers are employed to connect the integrated components.

The testing phase for this configuration, shown in Fig. 1.6, was divided into two distinct stages: an initial free-space implementation, designed to validate the filtering optics, followed by a transition to a fully integrated all-fiber layout. Initial alignment of this linear cavity was meticulously performed by temporarily substituting the SESAM with a highly reflective (HR) mirror to safely optimize intracavity losses and verify continuous-wave action. Once CW operation was established, the HR mirror was replaced with the hybrid “SESAM-in-air” setup. Initially, a standard flat-top bandpass filter (the previously employed dielectric filter) was inserted into the free-space section; however, the pulse train remained highly unstable. It became apparent that the instability in the previous ring topology was likely caused not only by the optical circulator but mostly by the intrinsic nature of the super-Gaussian spectral filtering itself. Consequently, a critical breakthrough was achieved by completely replacing the previous filter with a bulk diffraction grating arranged in a Littrow configuration. This optical element intrinsically provided a Gaussian spectral filtering profile with a full-width at half-maximum (FWHM) of approximately 8 nm (experimentally verified). With the grating in place, the free-space linear cavity immediately exhibited perfect, self-starting mode-locking. As systematically summarized in Table 1, the Gaussian filtering configuration outperformed the flat-top bandpass filter of comparable bandwidth. Specifically, the Gaussian filter expanded the pump-power

stability range to 100-320 mW, compared to the extremely narrow 280-300 mW window observed with the flat-top filter. Furthermore, the Gaussian profile supported broader intracavity spectra (~ 8 nm vs. ~ 7 nm) and enabled cleaner pulse compression down to ~ 350 fs, whereas the flat-top configuration was limited to ~ 430 fs. Complementary numerical simulations subsequently confirmed this empirical finding: in Yb-doped ANDi dissipative soliton oscillators, Gaussian spectral filtering significantly outperforms flat-top or super-Gaussian profiles, enabling a broader and more stable mode-locking regime.

	Gaussian filter 8nm FWHM	Band-pass filter 8nm FWHM
Pump-power stability range (mW)	100-320	280-300
Oscillator bandwidth (nm)	~ 8	~ 7
Compressed pulse duration (fs)	~ 350	~ 430

Table 1: Experimental comparison of oscillator performance employing Gaussian versus flat-top (super-Gaussian) spectral filtering.

It is highly probable that the initial ring cavity would have performed adequately had a tunable Gaussian filter been integrated instead of the super-Gaussian one; nevertheless, the linear topology was retained as the definitive architecture due to its mechanical simplicity and exceptional pulse train stability. Despite the optical success of the free-space setup, the inherent mechanical vulnerabilities and the extreme sensitivity to the focal plane positioning necessitated a complete transition to a better integrated architecture. The free-space components facing the SESAM were entirely removed, and the linear cavity was closed using commercial fiber-coupled SESAMs. The opposite end of the cavity maintained the collimator-to-grating arrangement to preserve the crucial Gaussian filtering dynamics.

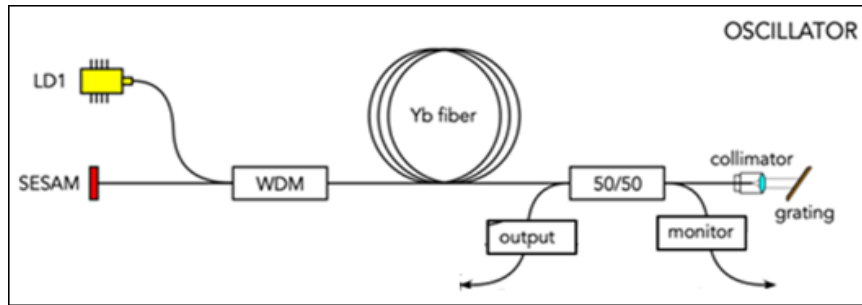


Figure 1.7 Schematic layout of the optimized linear standing-wave cavity after the transition to the integrated "SESAM-in-fiber" configuration. Right end of the cavity with free-space bulk diffraction grating (in a Littrow arrangement) to enforce the fundamental Gaussian spectral filtering components.

The final optimized linear layout, schematized in Figure 1.7, employed approximately 45 cm of active Yb-doped PM fiber to establish a fundamental repetition rate in the 22–25 MHz range. Crucially, the cavity incorporated a 50/50 PM fused fiber coupler. This specific component performs an indispensable dual function within the architecture: primarily, it acts as the main output port, extracting half of the circulating power to deliver

the laser signal. Simultaneously, the second port serves as a dedicated monitor channel. This monitoring line is essential for real-time diagnostics, as it enables the precise measurement of the spectral reflectivity profile generated by the combined fiber-collimator-grating system. To rigorously characterize this almost fully integrated linear cavity, an exhaustive comparative campaign was conducted. The setup was iteratively evaluated by using diffraction gratings with 300 grooves/mm and 600 grooves/mm to explore different reflection bandwidths, and by interchanging the physical absorbers. During this phase, two distinct commercial SESAM models were tested to evaluate the optimal modulation depth. The selected components were manufactured by BATOP GmbH (model: SAM), featuring a central wavelength of 1030 nm and a 1 ps relaxation time. The two specific models evaluated were SAM-1030-44-1ps and SAM-1030-54-1ps and they were systematically tested under identical pumping conditions. This new design enables the successful achievement of a mode-locking regime. This comprehensive evaluation was designed to understand the more stable mode-locking design and to verify the extensive wavelength tunability regions of the dissipative soliton regime.

SESAM Model	Wavelength Tuning (nm)	Spectral FWHM (nm)	Compressed Pulse (fs)
SAM-1030-44-1ps (Rep. Rate: 22 MHz)	1021 - 1034	7 - 9.5	320 - 400
SAM-1030-54-1ps (Rep. Rate: 20 MHz)	1021 - 1045	4 - 6	580 - 810

Table 1.2: Comparative experimental data detailing the performance and tunability metrics of the linear ANDi oscillator operating with two distinct fiber-coupled SESAM models.

The comparative analysis revealed distinct operational regimes as depicted in Table 1.2. While mode-locking was successfully achieved with both SESAM models, the configuration utilizing the SAM-1030-44-1ps proved marginally more stable with mode-locking running undisturbed for few hours. Tests also showed that while 54% absorbance SESAM provided a much broader wavelength tuning range (spanning up to 1045 nm), it generated significantly longer uncompressed pulses (up to 26 ps) and narrower optical spectra, yielding compressed durations clamped above 580 fs. Conversely, the 44% absorbance SESAM demonstrated superior spectral broadening (up to 9.5 nm) and

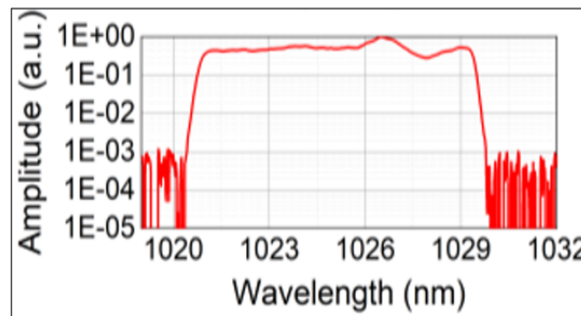


Figure 1.8 Output optical spectrum of the oscillator in the final linear configuration. The characteristic steep-edged "cat-ear" profile perfectly reflects the signature of the highly chirped dissipative soliton regime.

supported significantly shorter compressed pulses down to 320 fs when increasing the output power up to ~ 50 mW, albeit within a tighter tunability window before collapsing into continuous-wave operation at longer wavelengths.

The final optimized linear layout developed is a linear all-polarization-maintaining cavity with the SESAM SAM-1030-44-1ps placed at one end and a diffraction grating for 8 nm FWHM near-Gaussian filtering with 300 grooves/mm at the other and ensures a fundamental repetition rate in the 22–25 MHz range. Under these conditions the oscillator reliably delivered highly chirped pulses of ~ 10 ps duration with an average output power of 30 mW and a spectral bandwidth of ~ 8 nm. These pulses could be cleanly compressed externally down to 600–700 fs.

To validate the suitability of this source for high-power applications, the compressed pulses were then injected as a seed into a double-clad Yb-doped fiber amplifier working in the GMNA regime.

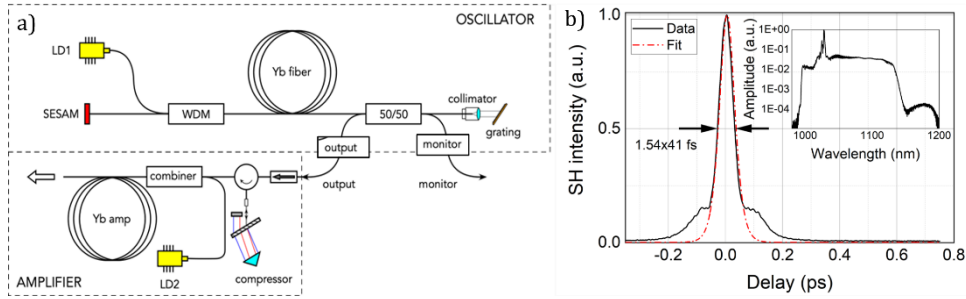


Figure 1.9 a) Scheme of the oscillator (up) and amplifier (bottom). b) Experimental second harmonic (SH) intensity autocorrelation of the amplified pulses after compression and sech2 fit. Inset: amplified spectrum.

When tested as a seed for a 4-m long Yb-doped fiber with GMNA Fig. 1.9a, the ANDi oscillator's narrower spectra and longer pulses (~ 10 ps) resulted in almost 20 times lower peak power than that from a MO with the same pumping conditions [20], preventing efficient direct amplification. However, after compression, the amplifier seeded by the ANDi source provided ~ 3 W output power and pulses as short as 40 fs (see second-harmonic intensity autocorrelation in Figure 1.9 (b), proving multi-watt ultrashort pulse generation in GMNA regime.

However, detailed analysis of the amplified output revealed the emergence of high-frequency spectral instabilities. It became evident that these instabilities in the amplified spectrum were highly likely manifestations of underlying instabilities originating within the oscillator itself, fluctuations that were visually imperceptible when observing the unamplified seed but were accentuated by the nonlinear amplification process. This is a critical issue for industrial translation, as transient loss of mode-locking or phase instabilities in the seed can easily induce irreversible optical damage in the amplifier. This stability issue was further compounded by the thermal limitations of the semiconductor absorbers observed over extended operational periods. During long-term testing involving repeated power cycling and wavelength tuning, a steady degradation in oscillator

performance was recorded. It is plausible, but requires further experimental investigation, that prolonged operation led to irreversible degradation of the SESAM lattice, primarily because these commercial components lack active thermoelectric cooling to manage the continuous thermal load. Consequently, the stabilization of the SESAM-based linear cavity remains an active area of investigation. Ongoing developments include the implementation of a dedicated thermal management system, involving a Peltier cell and a cooling fan integrated directly onto the fiber-coupled SESAM mount—and the complete environmental sealing of the cavity to mitigate thermal drifts, humidity, and potential atmospheric contamination (e.g., dust and grating oxidation). Because these stabilization protocols are still under development and the architecture cannot currently guarantee the reliable, long-term stability required for an industrial-grade laser source, the definitive architectural transition was made toward the MO, which bypasses the vulnerabilities of SESAMs entirely.

CHAPTER 2

2.1 Mamyshev Oscillator architecture

The MO operates as a direct evolution of the Mamyshev regenerator, functioning effectively as an artificial saturable absorber. The fundamental mechanism relies on a spectral filter that is deliberately shifted away from the central wavelength of the incoming light. As radiation propagates through a nonlinear Kerr medium, such as an optical fiber, only pulses with sufficiently high peak intensity experience strong enough SPM to spectrally broaden and reach the offset transmission band of the filter. On the contrary, low-intensity background noise and continuous-wave components lack the necessary peak power to induce SPM; thus, they fail to broaden and are completely blocked by the filter.

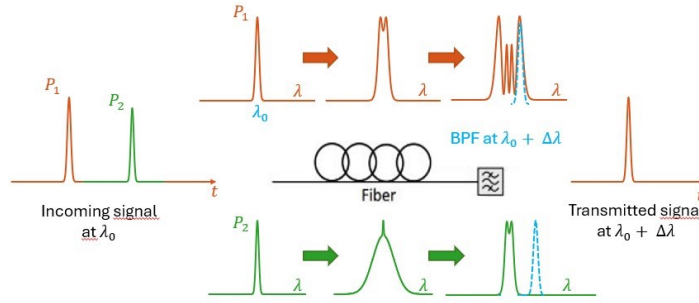


Figure 2.1 Example of a Mamyshev filter for regeneration of a signal.

This dynamic is visually described in Figure 2.1. Here, an intense signal (depicted in orange) and a low-power noise fluctuation (depicted in green), both initially centered at the exact same wavelength λ_0 , undergo nonlinear propagation. Driven by SPM, the high-power pulse spectrally broadens enough to overlap with the offset filter's transmission band (BPF at $\lambda_0 + \Delta\lambda$), allowing it to pass through. Meanwhile, the noise fluctuation does not broaden and is entirely extinguished, resulting in clean, high-contrast output signal.

By cascading two such regenerating stages equipped with completely non-overlapping spectral filters, it is possible to design a resonator that strictly and exclusively supports the

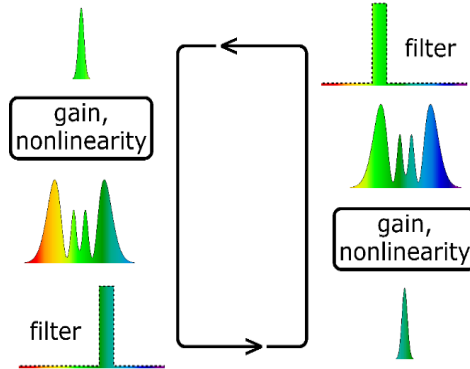


Figure 2.2 Conceptual scheme of a ring MO from [15].

circulation of high-intensity ultrashort pulses [13]. Figure 2.2 shows a conceptual ring layout where the signal undergoes SPM within the gain medium and is subsequently filtered in both arms. While Rochette [21] demonstrated early all-fiber versions of this oscillator, those initial designs were not tailored for high pulse energies. The energy-scaling potential of this architecture was effectively demonstrated by Regelskis, who achieved stable nanojoule-level picosecond pulses [16]. The conceptual layout of a standing-wave MO is illustrated in Figure 2.3.

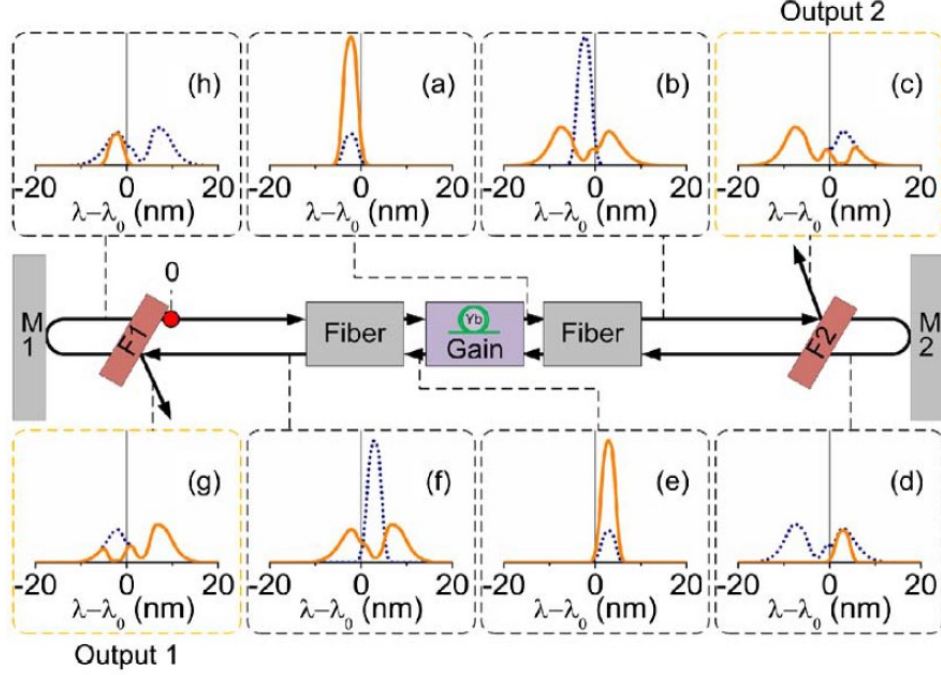


Figure 2.3 Pulse evolution in a standing-wave MO from [16].

The underlying mechanism of this linear configuration relies on a precise sequence of amplification, nonlinear broadening, and spectral filtering. The spectral evolution during a single cavity roundtrip is detailed in insets (a) through (h), where solid lines represent the current spectrum and dashed lines indicate the preceding state. Assuming a circulating pulse begins at point "0" near filter F1, it first propagates through the passive fiber and undergoes amplification in the Yb-doped active medium. Inset (a) displays the spectrum immediately post-amplification. As propagation continues through the subsequent passive section, the pulse's high peak power triggers strong SPM, leading to significant spectral expansion (b). Upon reaching filter F2, only a specific spectral slice is allowed to pass (d). The out-of-band components are rejected and can be extracted as the laser output (c). Because the transmission bands of F1 and F2 are completely offset with zero spectral overlap, the cavity exhibits an infinite loss state for any low-intensity radiation. A CW signal or low-power background noise, lacking the threshold peak power required to activate SPM, remains spectrally confined within the transmission window of F1 and is entirely blocked upon reaching F2. Conversely, an intense pulse undergoes high SPM-driven spectral broadening, generating new frequency components that bridge the spectral gap and pass through the offset window of F2. This intensity-dependent transmission mechanism functions as an artificial saturable absorber with an ideal, virtually infinite

modulation depth, completely suppressing the CW regime and forcing the system into stable mode-locked operation. After reflection at mirror M2, the pulse travels back through the active fiber, experiencing a second amplification stage (e). This energy boost enables the accumulation of additional SPM during the return trip (f), broadening the spectrum sufficiently to bridge the spectral gap back to the transmission window of F1. Filter F1 then transmits these newly generated wavelength components (h) and reflects the rejected portion toward Output 1 (g). Finally, the filtered pulse reflects off mirror M1 and is reinjected into the circuit to begin the next roundtrip. This continuous interplay of nonlinear spectral "breathing" and offset filtering rapidly converges to a stable steady state after a few iterations [16].

The architecture of the low-power MO, which was initially studied in the LSL at the University of Pavia and later evolved into the industrial prototype assembled at the company's facility, draws direct inspiration from the standing-wave layout first implemented by Regelskis [16], which is schematically illustrated in Figure 2.4.

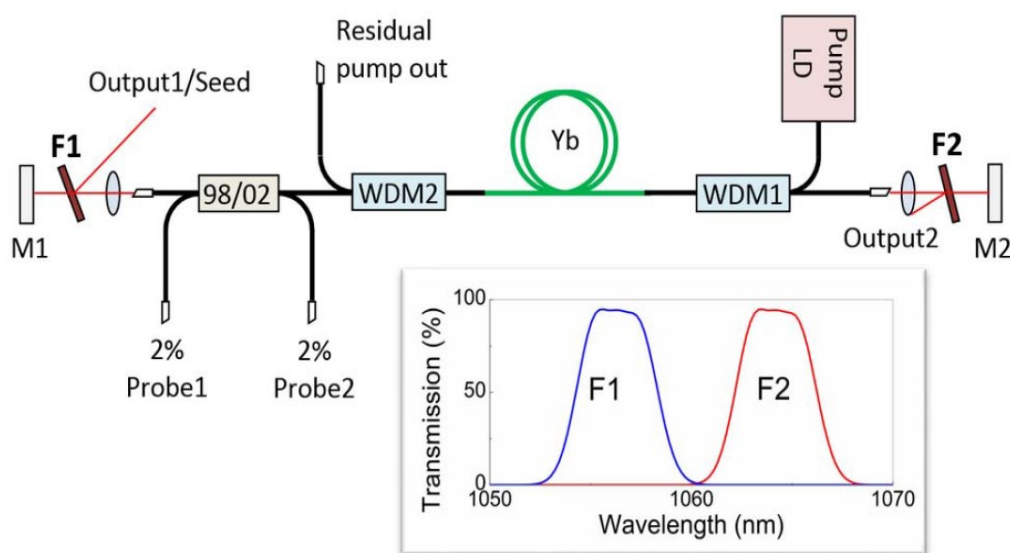


Figure 2.4 Practical implementation of a standing-wave Mamyshev oscillator [16].

In this configuration, the offset filtering is achieved through a pair of Super Gaussian (SG) transmission filters, labeled F1 and F2, whose spectral profiles are shown in the inset of Figure 2.4. Because the MO is not inherently self-starting, the mode-locking regime must be externally started. This is accomplished by injecting a single seed pulse, delivered by an external passively mode-locked picosecond fiber oscillator, through the Output 1/Seed port. Featuring a duration of 3 ps and an energy between 80 pJ and 1 nJ, this pulse provides the necessary initial peak power to ignite the pulse generation process within the MO cavity. The resonator utilizes a Yb-doped polarization-maintaining (PM) single-mode fiber as the active gain medium. Pumping is provided by a 976 nm single-mode fiber-coupled LD, injected via a first signal-pump multiplexer (WDM1), while any unabsorbed residual pump light is extracted by a second multiplexer (WDM2). Intracavity dynamics are

continuously monitored using a 98/02 fused fiber coupler; its 2% tap is also employed to measure the coupling efficiency of the injected seed pulse. The linear cavity is bounded by two highly reflective end mirrors that enclose the offset spectral filters [16].

2.2 Transition to an Industrial Architecture

The transition of the MO from an experimental laboratory setup to an industrial prototype device represents a critical operational prerequisite in its development. Extensive experimental activity conducted at the LSL established an experimental foundation for starting and sustaining the ML regime. The initial phases of this development were based on exhaustive experimental campaigns conducted by the LSL laboratory team. During these stages, the research group systematically analyzed the complex intracavity dynamics of a hybrid standing-wave setup. The experimental efforts focused primarily on optimizing the delicate balance between Kerr-induced spectral broadening, driven by SPM, and the strict spectral boundaries imposed by the offset transmission filters. Through these comprehensive investigations, the team successfully identified an optimal layout characterized by highly efficient and deterministic mode-locking, definitively validating the physical feasibility of the MO as the foundational seed source for an industrial MOPA system.

However, the intrinsically hybrid nature of these preliminary experimental setups presented insurmountable physical limitations for direct industrial deployment. The cavities analysed during this phase consistently relied on free-space bulk optics at their terminal ends. Depending on the specific layout under investigation, these discrete components included diffraction gratings arranged in a Littrow configuration, super-Gaussian transmission filters, and standard dielectric mirrors.

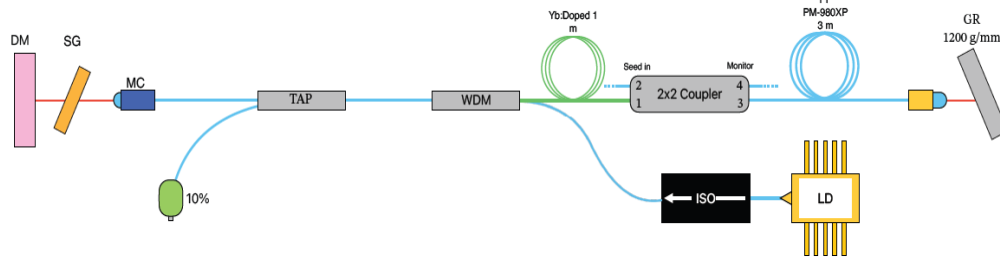


Figure 2.5 Standing-wave cavity with Super Gaussian and Diffraction grating as offset spectral filters. DM: Dielectric mirror. SG: Super Gaussian filter. LD: Laser Diode. GR: Diffraction grating in Littrow configuration. ISO: Optical Faraday Isolator.

To experimentally transition the MO into an industrial prototype, the LSL team conducted extensive research aimed at fully optimizing the optical layout. Within this context, the precise configuration of the offset spectral filters emerged as a fundamental engineering challenge. Experimental investigations demonstrated that the optimal spectral separation between the intracavity filters for reliable ML operation is approximately 4 nm, with the transmission bands centered at 1032 nm and 1036 nm. This specific parameter was adopted as a strict design rule during the physical assembly of the prototype at the company's facility.

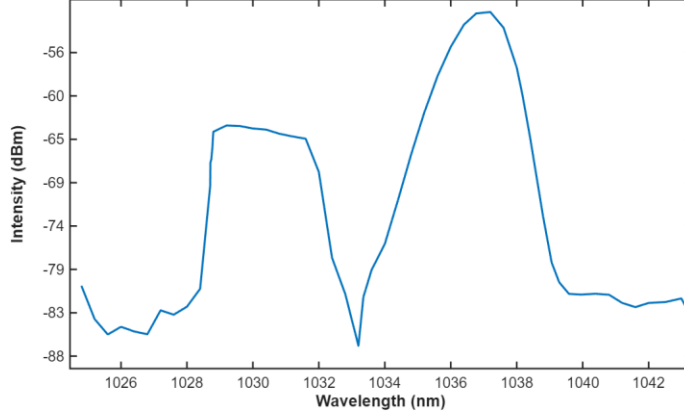


Fig. 2.7 Optical spectra of the two filters.

The exact filter separation directly dictates the amount of seed energy required to initiate the ML regime and fundamentally shapes the temporal and spectral properties of the desired output pulse. Through this optimized engineering compromise, combining a fixed, alignment-free integrated BPF and FM on one side with a highly tunable diffraction grating on the other, the newly designed oscillator achieved highly reliable mode-locking. Ultimately, these factors solidify this layout as the optimal configuration for an industrial-prototype MO.

2.3 Seeding setup and its evolution

The spectral separation of the two offset filters in a MO strictly dictates its energetic performance. A larger separation allows for higher pulse energies and broader bandwidths driven by SPM. However, this wide separation inherently prevents the ML regime from self-starting [13]. While several initiation techniques exist, such as dynamic filter tuning, pump modulation, or polarization adjustments, the most deterministic approach is to inject an external seed pulse. Conventionally, this requires a complex and expensive mode-locked laser capable of delivering picosecond, nanojoule-level pulses to trigger SPM within a single cavity round-trip [16]. To overcome the high complexity and footprint of traditional seeding, a reliable and cost-effective alternative was validated by the LSL [15]. This technique utilizes a diode-pumped, passively Q-switched (PQS) Nd:YAG/Cr:YAG microchip laser that emits sub-nanosecond, single-longitudinal-mode (SLM) pulses at 1064 nm. This specific wavelength is standard for sub-ns microchip lasers due to the excellent passive Q-switching properties of the Nd:YAG architecture, making the source extremely simple and affordable. When these kilowatt-peak-power pulses are injected into a standard single-mode PM fiber, they undergo non-phase-matched four-wave mixing (FWM) in the normal dispersion regime. This nonlinear process generates a broad spectral pedestal extending approximately ± 10 nm around the 1064 nm pump. Within the sub-nanosecond temporal envelope, this pedestal contains ultrafast noise fluctuations that, once amplified in the active medium of the MO cavity, rapidly accumulate sufficient SPM to bridge the offset filters and stably start the ML regime [15]. Although the MO can be started at the nominal 1064 nm wavelength emitted by the PQS, Figure 2.8 highlights that this

wavelength its far from the gain peak of Ytterbium-doped silica fibers, which is located around 1030 nm. This observation suggests that the overall performance of the MO can be significantly optimized by shifting the seeding wavelength closer to the peak of the active gain medium. This can be beneficial also in view of a subsequent amplification of the pulses produced by the low power MO in a Yb-doped fiber amplifier, since the MO pulse spectrum tends to be around the seeding wavelength, since it is fixing the region in which the two offset spectral filters are adjusted. So, to maximize the MO efficiency and perfectly match the gain peak for subsequent amplification stages, the seeding wavelength must be shifted by exploiting phase-matched DFWM within a highly birefringent PM fiber.

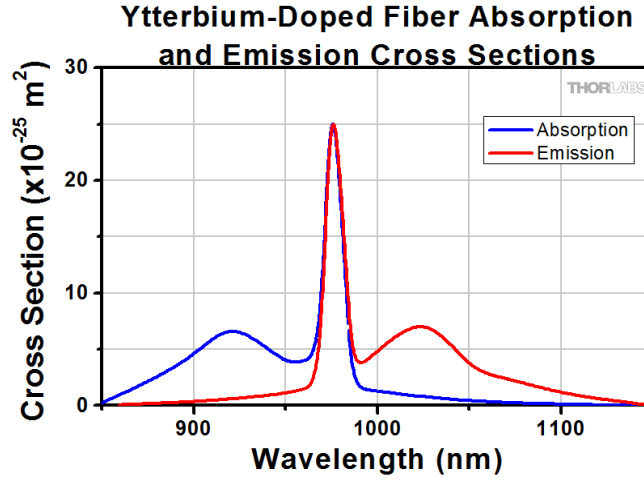


Figure 2.8 Emission and absorption cross-section for Yb-Doped active fiber. Image provided by Thorlabs website.

This is made possible by the cubic term in the nonlinear polarization, under the so-called “phase matching condition”, shown in figure 2.9 (a), which describes a momentum conservation for the interactive photons. In DFWM, two photons at the pump frequency ω_p are annihilated in order to generate one photon at ω_s (signal photon) and one at ω_i (idler photon).

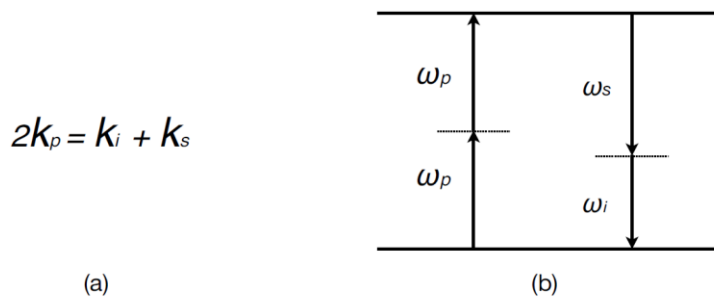


Figure 2.9 a) Phase Matching condition b) Jablonski diagram for DFWM.

By launching the linearly polarized 1064 nm pump pulses at 45° relative to the birefringence axes of the PM-980-XP fiber, the phase-matching condition $2k_p = k_s + k_i$ is satisfied, consequently, driven by the birefringence and material dispersion of the fiber, this process efficiently annihilates two pump photons to generate a signal photon at ~1033

nm (polarized along the slow axis) and an idler photon at 1098 nm (polarized along the fast axis) as shown in figure 2.10. As the injected pump energy increases, these DFWM sidebands experience significant spectral broadening which is a fundamental prerequisite for activating the Mamyshev filtering mechanism. Employing this strategy, we are able to start the ML regime within the MO cavity, matching the gain peak of the Ytterbium-doped silica active fiber.

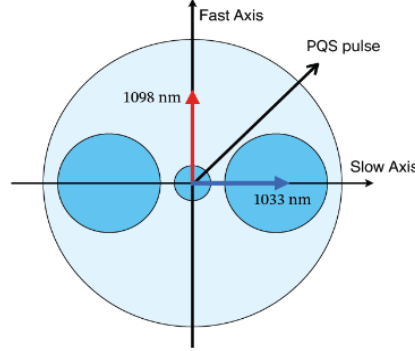


Figure 2.10 PM panda fiber cross-section. Seed pulse polarized at 45°. Signal (1033 nm) polarized along Slow axis. Idler (1098 nm) polarized along Fast axis.

To reliably engineer the seeder making it suitable for an industrial-grade device, the comprehensive characterization of the DFWM process and of the layout previously performed at the LSL served as the fundamental quantitative guideline. The goal was to establish the ideal seeding conditions required to start the mode-locking regime and then replicate them in the final version of the seeding stage. In the initial laboratory setup (Fig. 2.11), a PM panda fiber (PM-980-XP) was selected to efficiently transfer energy into the DFWM band. Theoretically, considering a birefringence δn of approximately 2.7×10^{-4} and a material dispersion k_p'' of $17 \text{ fs}^2/\text{mm}$ for this specific fiber, the expected wavelength shift is calculated:

$$\Delta\lambda = \frac{\lambda_p^2 \cdot \delta n}{2\pi c \cdot k_p''} \approx 33 \text{ nm}$$

Using a 12-m long fiber, as we can see in Figure 2.11, the laboratory experiments generated the two sidebands at 1033 nm and ~ 1100 nm. Considering that the exact signal wavelength is not a critical constraint, as the true requirement is that the real emission peak has to fall well within the acceptance bandwidth of the inline filters, preserving high seeding efficiency and a low mode-locking threshold. To rigorously characterize the temporal profile of these wavelength-shifted pulses, measurements were conducted using a 6-GHz oscilloscope (Tektronix TDS6604B) coupled with a 70-ps rise-time fast photodiode.

The results demonstrated that the 1033 nm signal pulse experienced a significant nonlinear compression by a factor of roughly three compared to the initial pump, resulting in approximately 180 ps of duration ($\Delta\tau_{sig}$). Conversely, the idler pulse duration ($\Delta\tau_{idl}$) was estimated at 300 ps. Operating with a conversion efficiency of a few percent, this

architecture delivered 0.5–2 nJ pulses directly at 1033 nm. Although a pulse duration of 180 ps is significantly longer than the typical 3 ps seed conventionally reported in literature [16], LSL laboratory campaign successfully demonstrated that such extended pulses are highly effective for ML initiation. Physically, the starting mechanism does not strictly depend on the global, macroscopic pulse width, but rather on the local peak power of the temporal substructures. Because the seed is generated by a kilowatt-peak-power PQS microchip laser, the resulting 180 ps envelope is highly structured, containing ultrafast sub-picosecond noise fluctuations and high-intensity spikes. When coupled into the high-gain Ytterbium-doped active fiber of the MO, these localized high-peak-power spikes undergo immediate and high SPM. These intense spikes generate the necessary spectral components to bridge the non-overlapping filter gap just as effectively as a transform-limited 3 ps pulse, thereby starting stable, self-sustaining mode-locked operation. These precise temporal and energetic metrics, specifically the 180 ps pulse duration and the nJ-level energy at 1033 nm, served as fundamental benchmarks during the later study phases of the seeder. The initial design deliberately prioritized a thorough investigation of the seeding dynamics and the optimal conditions for mode-locking initiation over compactness or engineered packaging. In the laboratory configuration, shown in Figure 2.11, the free-space beam emitted by the PQS seeder propagates through a Half-Wave Plate (HWP) to precisely set the 45° injection angle, thereby initiating the DFWM process within the fiber and so reliably generating the 1033 nm and 1100 nm sidebands through the non-linear process. Once the two tones are generated, the radiation exits back into free space, where a spectral filter isolates the specific wavelength of interest before a micro-collimator couples it back into the fiber. Finally, the 1033 nm signal, already partially broadened by the nonlinear process, is injected into the cavity via port 2 of the 2x2 coupler and is immediately routed through port 1 directly into the active fiber. This routing is a specific design choice: it ensures the seed pulse undergoes immediate amplification, acquiring sufficient peak power to activate further SPM before encountering the first spectral filter.

This allows a fraction of the newly broadened spectrum to fall within the filter's transmission band and reflect back into the cavity to seed the oscillation.

Once it was established that the DFWM-generated pulses could reliably start the oscillator, a dedicated investigation was conducted to determine the absolute minimum seed pulse

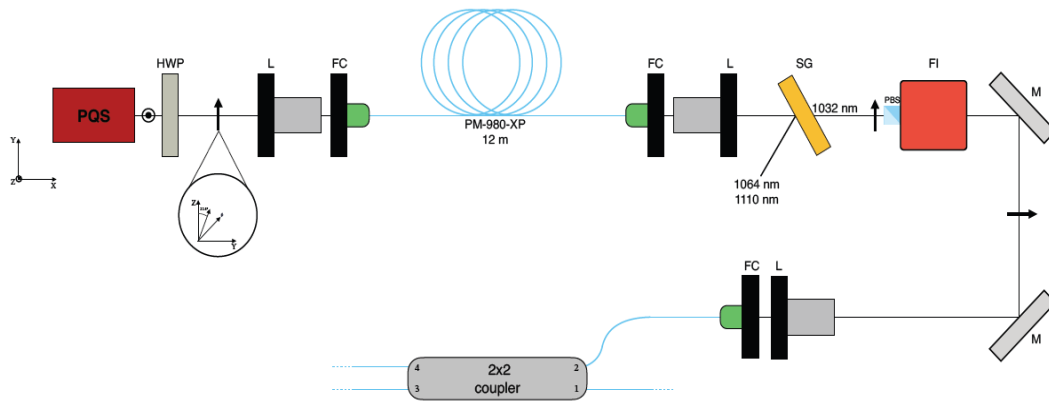


Figure 2.11 Seeder setup. PQS: passively Q-Switched Nd:YAG/Cr:YAG microchip laser at 1064 nm. HWP: half wave plate with its optic axis at 22.5° with respect to z. L-FC: Fiber collimator.

SM: Single mode PM passive fiber 12 m. SG: angle tuned super-gaussian filter.

PBS: Polarization beam splitter. FI: Optical Faraday Isolator. M: metallic mirror

energy required to ignite the self-sustaining ML regime. Considering the system's coupling efficiencies and internal component transmissions, the effective minimum pulse energy reaching the active medium required to initiate ML was calculated to be just 20 pJ. This low threshold highlights that: while the absolute energy required to trigger the oscillator is remarkably small (on the order of tens of picojoules), the initial spectral broadening of the seed pulse, driven by the high peak power of the PQS laser, is the primary prerequisite for mode-locking initiation. Since the seeder delivers nanojoule-level pulses at 1033 nm, the available pulse energy exceeds the 20 pJ mode-locking thresholds by over two orders of magnitude, providing an extensive operating margin and this was a key factor in the subsequent engineering phase. It provided the confidence to streamline the seeder layout and transition toward an all-fiber design. Even if these simplifications resulted in a reduction of the delivered seed energy due to higher insertion losses or less optimal coupling, the system was guaranteed to remain well above the energy threshold, ensuring efficient and reliable ML initiation. The preliminary laboratory layout relied on a multitude of discrete components with significant free-space propagation, an arrangement that was perfect for establishing these operational benchmarks, but too complex for an industrial device. This reliance on bulk optics as we know makes the system inherently sensitive to misalignment, vulnerable to environmental perturbations, and fundamentally unsuitable for practical field deployment. Because industrial prototyping demands rigorous opto-mechanical stability, high efficiency, and a minimal footprint, the setup shown in Figure 2.11 served as a diagnostic experimental baseline. Before transferring the assembly to the company's facility, the primary objective was to redesign the initial layout into a compact and environmentally stable all-fiber injection stage.

The final seeding stage preserves the reliable physical mechanism validated in the laboratory but implements a simplified injection scheme tailored specifically for the industrial prototype. The final seeder layout, illustrated in Figure 2.12, utilizes the same 1064 nm PQS laser, provided by Bright Solutions srl, which delivers 490-ps-long, SLM, linearly polarized pulses at a repetition rate of 55 kHz. The guiding engineering principle was to reduce the system to its absolute simplest form so to achieve this, the free-space pulses emitted by the PQS laser are directly coupled into the fiber using only two adjustable mirrors and a micro-collimator. This minimalist arrangement provides the precise mechanical degrees of freedom required to guarantee optimal alignment into the PM fiber completely eliminating the need for complex, intermediate free-space optics.

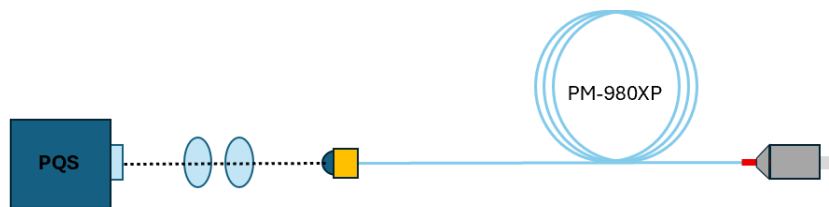


Figure 2.12 Seeder setup. PQS: passively Q-Switched Nd:YAG/Cr:YAG microchip laser at 1064 nm. L-FC: Fiber collimator. SM: Single mode PM passive fiber (~12 m).

Once coupled by the micro-collimator, the radiation propagates through the passive PM-980-XP fiber to drive the non-linear process, delivering the necessary broadened trigger pulse. As previously discussed, the injected polarization state, and consequently the launch angle into the birefringent fiber, is a key step to do. The primary advantage of this integrated layout is the complete elimination of discrete, free-space polarization optics, such as waveplates, super-Gaussian filters, and polarizing beam splitters. In this compact configuration, the system generates the two desired phase-matched sidebands at 1033 nm and 1100 nm simply by coupling adequate pulse energy into a specific length of passive fiber. The required 45° launch angle is adjusted by rotating the MC within its mounting holder, aligning the fiber's principal birefringence axes with the polarization vector of the incident beam. This streamlined conceptual layout was further refined and adapted to strictly comply with the mechanical constraints of the final industrial packaging. Comparing this new configuration with the preliminary laboratory setup shown before in Figure 2.11, it is evident that the optical design underwent a systematic simplification without compromising performance. This optimized approach significantly enhances the compactness and long-term reliability of the prototype.

CHAPTER 3

Practical implementation of the MO industrial prototype injected by sub-ns pulses at 1033 nm

This chapter describes the physical architecture of the MO prototype assembled inside the company's cleanroom facility, presenting the key experimental results obtained during its implementation. As detailed in the previous chapter, this assembly phase was preceded by the analysis of the cavity architecture and the seeding mechanism, conducted primarily by the LSL team. While I took part in the final testing stages of the optimized seeder, the transfer from a laboratory setup to a real prototype required a continuous collaboration between the university and the company. This joint effort was focused on engineering the optical layout, designing the best opto-mechanical packaging, managing the electronics, and finalizing the component list. Once the engineered design was defined, the components were delivered, and the workspace in the cleanroom was ready, I began the physical assembly of the prototype.

3.1 Characterization of the oscillator pump module

The assembly of the industrial prototype began by defining and characterizing the primary pump source for the laser oscillator. A 400-mW single-mode fiber-coupled butterfly LD (Box Optronics BFLD-976F-4HSMNO) stabilized by an integrated FBG at 976 nm was selected. Because the diode features wavelength stabilization and operates at a relatively low maximum injected current ($I_{max} = 600$ mA), it does not require an active temperature control system.

Fig. 3.1 report the measured LD output power as a function of the driving current. The device's optical behavior follows the typical linear response for this class of semiconductor components. The lasing threshold was observed at a driving current of approximately 72 mA (corresponding to 12% on the driver interface). Above this threshold, the output power increases linearly with a slope efficiency of roughly 0.75 mW/mA, delivering a maximum measured power of 385 mW at the nominal operating current of 600 mA.

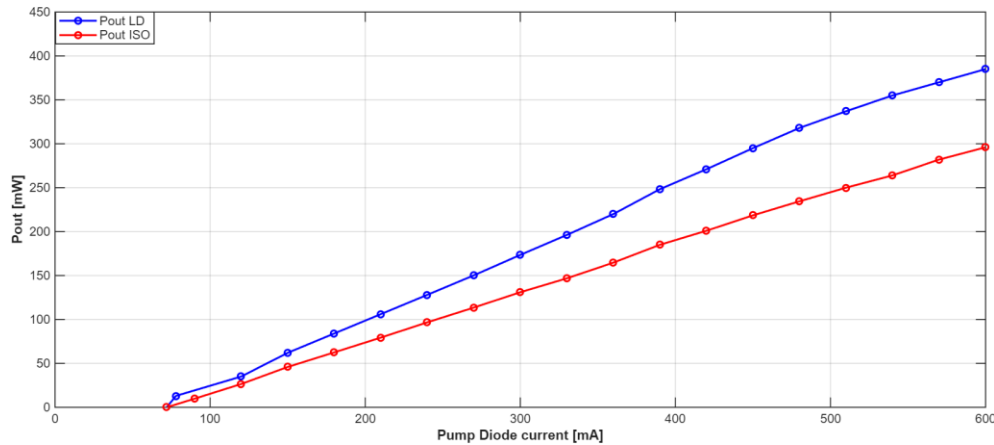


Figure 3.1 LD output power as a function of the driving current, in blue, and in red the output power measured after the fiber-coupled FI.

To safeguard the LD against detrimental back-reflections or destabilizing backward-propagating signals originating within the resonator, a fiber-coupled FI was fusion-spliced immediately after the diode pigtail, preceding the WDM. The introduction of this component results in a noticeable decrease in the overall slope efficiency as can be seen in Fig. 3.1, due to its inherent insertion losses. By comparing the maximum output power directly from the diode (385 mW) with the power measured after the isolator (296 mW), the actual insertion loss for this specific device was calculated to be approximately 23%. Consequently, the effective slope efficiency drops to roughly 0.56 mW/mA, delivering a maximum available pump power of 296 mW at the nominal driving current of 600 mA. Finally, the pump radiation is coupled into the cavity via a Seagnol PM 980/1030 WDM. To evaluate the coupling efficiency of this final injection stage, the optical power was characterized at the output of the WDM, which represents the actual pump power delivered and available for absorption by the active gain medium. It is important to note a structural constraint in this section of the pump module: the WDM is pigtailed with a PANDA PM-980-XP single-mode fiber, whereas the preceding FI is equipped with a standard non-PM single-mode fiber. Fusion splicing these two dissimilar fibers inherently results in sub-optimal joint compared to a standard PM-to-PM splice, inevitably introducing slight mode-field mismatches and localized scattering losses. By comparing the maximum optical power measured immediately before the WDM (296 mW) with the power measured at its output (260 mW at the maximum nominal driving current), we can evaluate the efficiency of this final injection stage. The total transmission of the WDM, encompassing both the component's internal insertion loss and the dissimilar splice loss, is calculated to be approximately 87.8%.

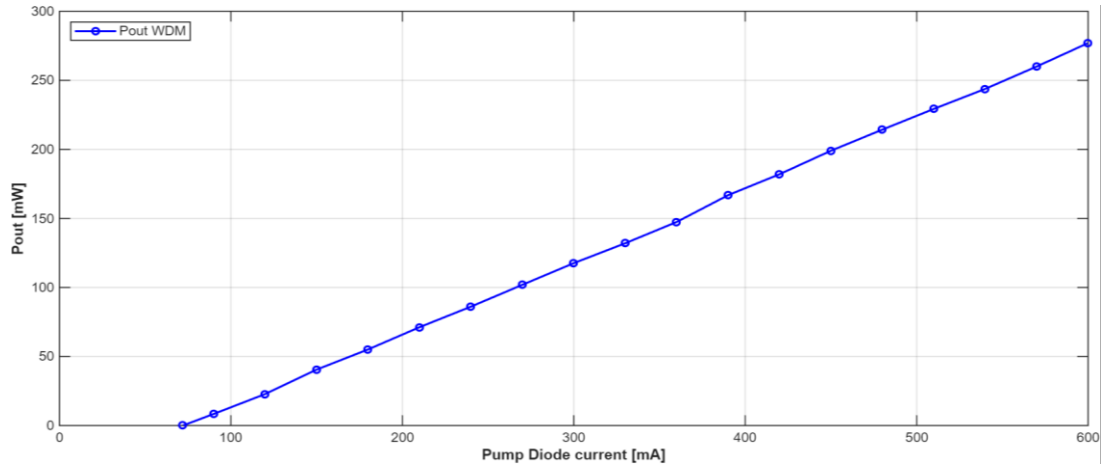


Figure 3.2 power output from the WDM.

The whole pump module is shown in Fig. 3.3.

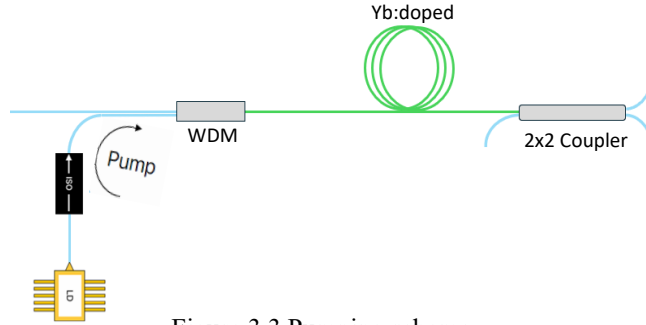


Figure 3.3 Pumping scheme.

3.2 Implementation of the standing-wave hybrid oscillator in CW regime

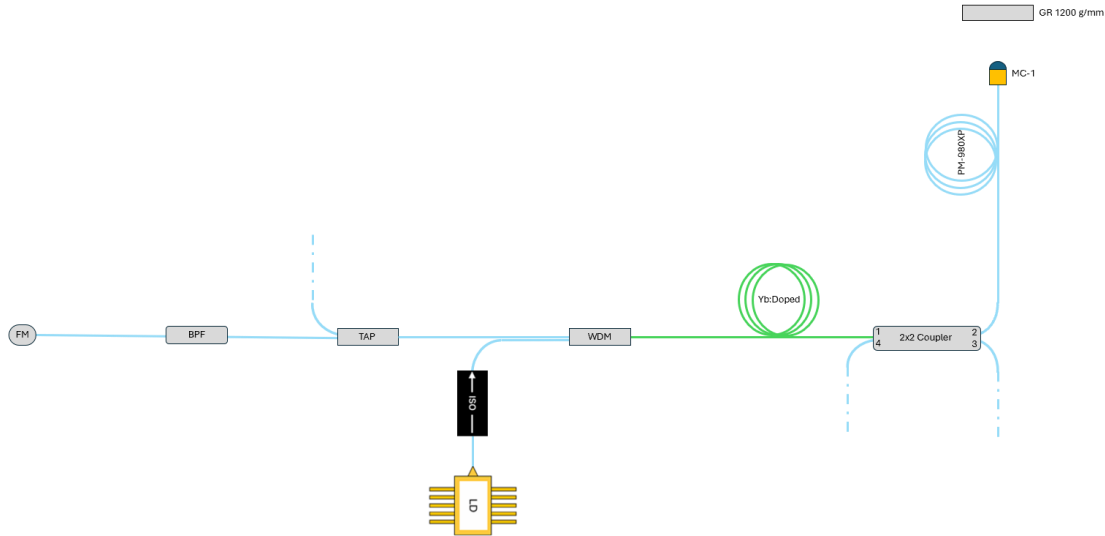


Figure 3.4 Fiber laser cavity setup.

After installing the pumping module, the integration of the internal cavity components proceeded by splicing the active gain medium to the WDM. The active section consists of 1.2 meters of PM Yb-doped fiber (Thorlabs YB300-6/125-PM). Although this fiber is nominally core-matched with the passive PM-980-XP fiber utilized throughout the rest of the cavity, the fusion splicing of the highly-doped Yb active fiber to the passive PM- 980- XP fiber required precise optimization of the arc duration and power to prevent mechanical fragility and micro-defects at the splice interface. Initial attempts frequently resulted in mechanical weakness, often failing the splicer's automated tension strain test, or revealed microscopic bubbles and localized hotspots on the monitors. An imperfect splice at this junction acts as a scattering point, causing localized losses and generating unwanted back-reflections that, even during preliminary CW testing, tended to induce self-lasing through spurious parasitic cavities. To overcome these early issues, it became clear

that meticulous fiber preparation was essential. Strict attention was paid to the quality of the fiber cleave and its precise positioning within the fusion splicer. Additionally, to ensure consistent and reliable arcs, regular machine recalibrations were performed after a set number of splices. Whenever a splice resulted in sub-optimal transmission or structural integrity, several centimeters of fiber had to be cleaved to repeat the procedure. While reducing the length of a passive transport fiber is generally inconsequential, altering the length of the highly doped active fiber directly modifies fundamental design parameters, affecting the total gain and dispersion. This length constraint was particularly critical: although we were initially implementing the CW cavity, the total physical length of the optical path had to be strictly managed to meet the final project requirement of a fundamental repetition rate around 10 MHz. This physical limit also applied to the fiber-integrated components with fixed pigtail lengths, where excessive re-splicing could eventually make them unusable.

Following the active section, a Seagnol 30/70 2x2 PM coupler was integrated. Its primary ports manage the bidirectional signal within the standing-wave cavity, splitting the circulating optical power to retain a portion for cavity feedback while extracting the rest for amplification and monitoring. The semi-integrated cavity topology simplifies the optical alignment by preserving wavelength tunability. The PM passive fiber is terminated with a precisely aligned micro-collimator ($f = 2$ mm). To isolate the free-space beam from the external environment, the packaging features a specifically designed isolated cubic housing. Upon exiting the micro-collimator, the radiation propagates entirely within this enclosed environment before striking a bulk diffraction grating (Thorlabs GR25-1210, 1 μ m blaze wavelength, 1200 grooves/mm) arranged in a Littrow configuration. This custom-designed housing effectively functions as a mechanical cage, shielding the grating and the unguided optical path from air turbulence, dust particles, and acoustic vibrations that would otherwise destabilize the overall coupling efficiency. Furthermore, to guarantee the exact same level of environmental stability, this protective enclosure is designed to simultaneously house the diffraction grating dedicated to the subsequent amplification stage. The reflective diffraction grating required careful opto-mechanical integration. To simplify the alignment process and ensure maximum stability, the grating was glued onto a custom square mount using Dymax OP-61 adhesive. The side of this square mount was designed to be exactly equal to the grating's outer diameter, allowing the optical component to be perfectly inscribed and centered. Once the optimal position was achieved, the assembly was irradiated with UV light to definitively cure the glue and rigidly secure the grating in place. Subsequently, the square mounting support was installed within the protective enclosure. With the right arm of the cavity fully assembled, the integration of the components continued on the opposite side, moving to the left of the WDM, as depicted in Figure 3.4. The first component in this section is a dedicated 90/10 PM tap coupler. The 90% port maintains the signal within the cavity, while the 10% output port is terminated with an Angled Physical Contact (APC) connector to allow for direct coupling with the external seeder stage via a mating sleeve. Following the tap, the optical path enters the completely fiber-integrated arm, terminating in an inline band-pass filter (Seagnol PMBPF-1030-02-06-B-10-NE) directly spliced to a highly reflective Fiber Mirror (Seagnol FMR-1030-PM-B-10-FA). This configuration creates a zero-alignment, highly robust reflection

boundary immune to mechanical vibrations and dust, where the BPF's steep spectral edges accurately dictate the reflection bandwidth and anchor the circulating optical signal. After all the elements were spliced and integrated, the CW pump diode was activated to start oscillation. On the free-space arm, the bulk grating was finely angle-tuned adjusting its horizontal tilt via high-precision kinematic controls to back-reflect the signal directly into the micro-collimator core and also, similar to the seeder alignment procedure, the micro-collimator itself was physically rotated around its optical axis to match the optimal polarization state, thereby maximizing the coupling efficiency. Throughout this process, the reflection wavelength was actively monitored using an Optical Spectrum Analyzer (OSA). The initial alignment was adjusted to achieve the lowest possible lasing threshold. Once the back-coupling was maximized, the system demonstrated robust CW oscillation, validating the cavity's integrity and enabling the progression to the mode-locking tests after the installation of the seeding stage.

3.3 Seeder design

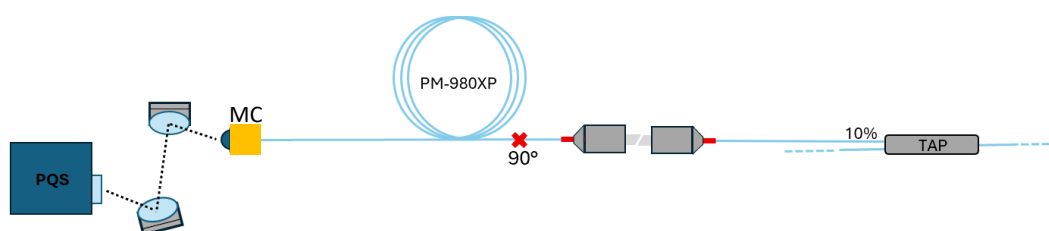


Figure 3.5 Optimized Seeder setup.

Following the experimental validation of the CW cavity, the optimized seeder layout was implemented. This optimized layout was assembled for the first time directly at the company's facility. It preserves the reliable physical mechanism tested in the laboratory, but to precisely couple the free-space beam into the fiber, it employs two mirrors mounted on kinematic flexure mounts in a Z-fold configuration. This geometric arrangement significantly minimizes the spatial footprint while providing the exact degrees of freedom required to achieve optimal alignment into the PM fiber micro-collimator. During the assembly of the CW cavity, a polarization dynamic was addressed: the inline optical components inherently act as fast-axis blockers, meaning that the injected signal must be aligned with the slow axis of the resonator. Because the seeder fiber termination requires an APC connector for physical coupling to the cavity's 10% tap port, a fixed geometric orientation was imposed. However, this angled connector configuration introduced an orthogonal polarization offset relative to the cavity's transmission axis. To compensate for this mismatch and align the polarization vector of the seed, a fundamental 90° splice rotation was implemented between the PM fiber of the seeder and the PM fiber segment terminating with the APC connector. This rotation compensates for the orthogonal offset between the mechanical alignment key of commercial FC/APC connectors and the birefringence axes of the PM fiber. This configuration successfully maps the 1033 nm seed

directly onto the slow axis of the cavity, preventing the signal from being blocked by the fast-axis-blocking inline components and ensuring efficient mode-locking initiation. During the integration phase inside the company's cleanroom, optical characterizations were performed to verify that this newly optimized seeder layout could reproduce the ideal mode-locking starting conditions originally established at the LSL. The measurements confirmed that the industrial system matched the laboratory baselines, demonstrating that this simplified and robust seeder ensures a deterministic and optimal initiation of the ML regime.

Finally, a physical optical connector was integrated as the interface between the seeding stage and the 10% port of the tap coupler. This modular configuration facilitates maintenance and allows direct diagnostic access to the seeder's output, eliminating the need to repeatedly break and re-splice the optical fibers during calibration.

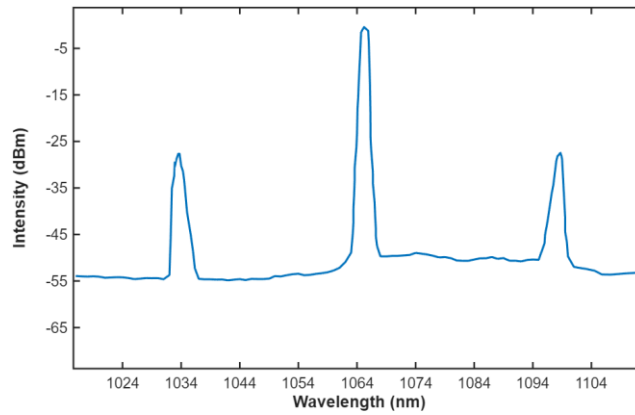


Figure 3.6 DFWM spectrum power.

This new layout is highly suited for the industrial prototype due to its simplicity, robustness, and compact footprint, while still providing excellent generation of the two DFWM sidebands. As an example, Figure 3.6 displays the DFWM spectrum acquired during the alignment phase at the company's cleanroom facility, clearly showing the three distinct spectral tones. Once it was verified that the energy delivered to the tap input remained well above the picojoule-level threshold, and that the correct polarization and target wavelength were maintained, the high efficiency of this engineered and simplified layout in generating the 1033 nm signal was fully confirmed. With these parameters validated, the seeding stage was ready to be physically connected to the main cavity to proceed with the final verification of the mode-locking initiation.

3.4 Cavity design

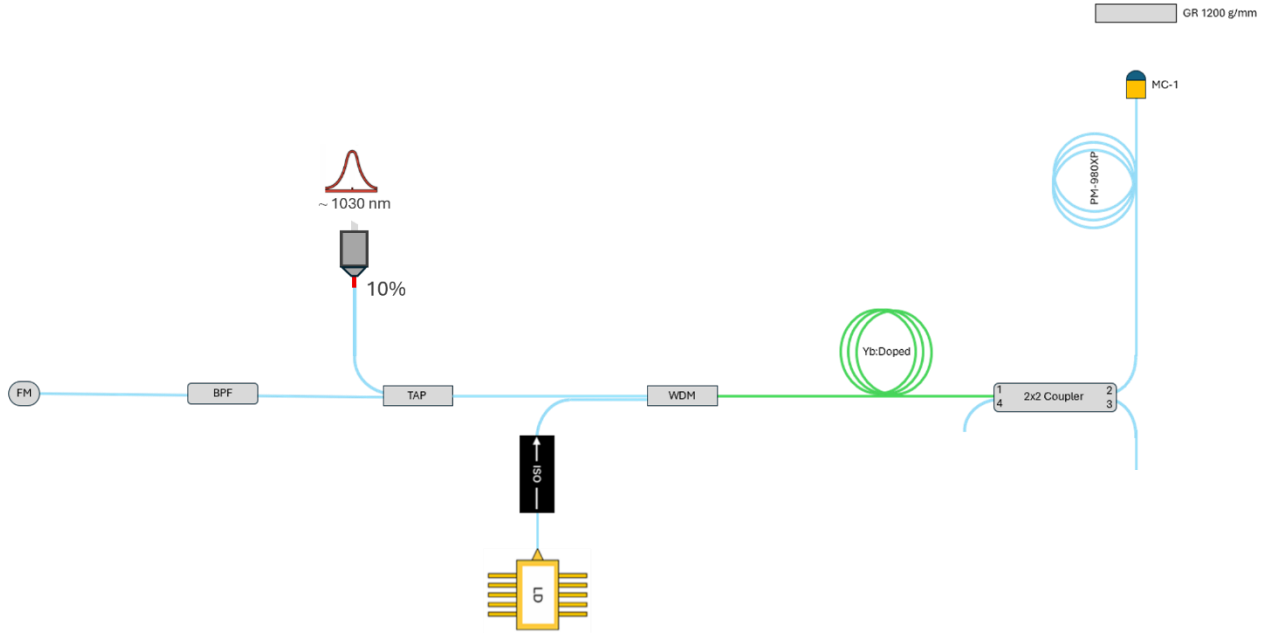


Figure 3.7 Final hybrid cavity configuration.

With both the continuous-wave cavity and the final seeding stage experimentally assembled, the two subsystems were physically interfaced by connecting the seeder output to the 10% port of the tap coupler. To monitor the initiation and stability of the ML regime without disrupting the cavity dynamics, the initial cavity layout exploited the fourth port of the 2x2 PM coupler as an auxiliary diagnostic channel. While 70% of the forward power was extracted as the main output, the 30% port was routed to the diffraction grating for cavity feedback. When the signal reflected from the grating re-entered the coupler, the backward-propagating power was split, directing 70% of this feedback signal to the auxiliary port on the input side. This configuration allowed for the simultaneous characterization of the main output power and the real-time monitoring of both the spectral evolution (via an OSA) and the time-domain pulse train (via a fast photodiode and oscilloscope). During these diagnostic procedures, strict operational protocols were enforced when connecting and disconnecting the fiber tips to the OSA and the photodiode. Based on prior laboratory experiences where optical components and fiber tips, even those utilizing APC terminations, suffered irreversible optical damage, the pump laser was systematically turned off prior to any physical manipulation of the connectors. Plugging or unplugging a fiber while the laser is operating inevitably exposes the core to a sudden glass-air interface, generating unwanted back-reflections. In this high-gain system, these unseeded reflections can propagate backward into the active fiber, undergo huge amplification, and easily exceed the damage threshold of the components along the optical chain. By systematically adjusting the spectral separation between the offset filters while scaling the pump diode power the dynamic behavior of the MO was thoroughly

characterized. Once the ML regime was initiated in this preliminary setup, the average output power was characterized as a function of the pump diode driving current. These initial quantitative results, corresponding to an unoptimized cavity configuration operating at a repetition rate of 10.07 MHz, are summarized in Figure 3.8.

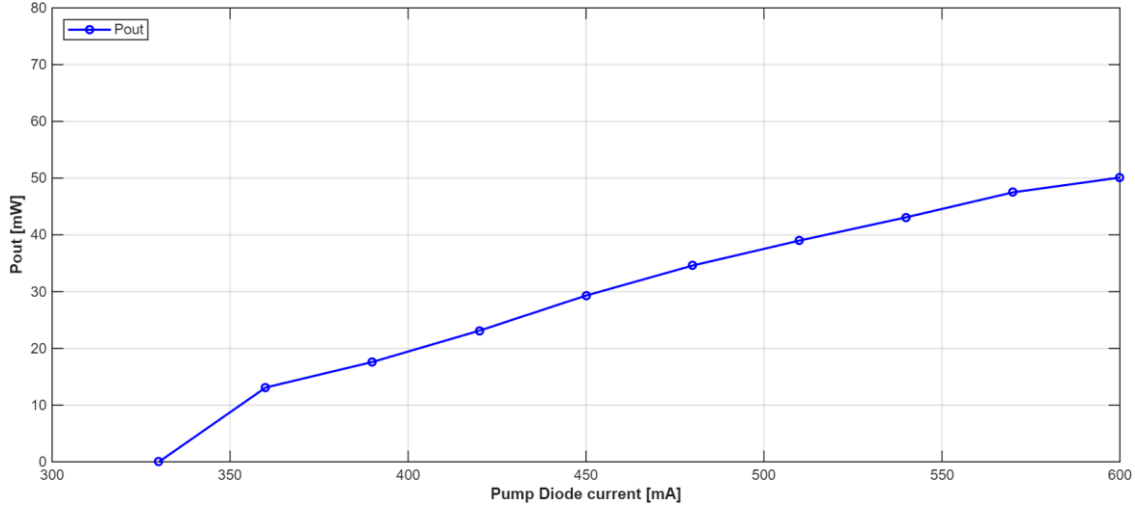


Figure 3.8 Average output power as a function of the pump laser diode driving current for the initial configuration operating at a repetition rate of 10.07 MHz.

During the initial power characterization and subsequent tests, increasing the pump driving current beyond a fluctuating threshold of approximately 70% to 80% systematically triggered instabilities in both the spectrum and the pulse train. Notably, the system exhibited occasional double-pulsing and a strong tendency toward CW emission at 1030 nm. Similar phenomena were documented during early laboratory investigations, where CW operation was attributed to the spectral overlap of the offset filters. If these filters are tuned too close together, or if their Gaussian tails are excessively broad, the intracavity radiation circulates without undergoing sufficient spectral broadening via SPM, blocking the initiation of ML. Considering the well-established opto-mechanical architecture and spectral parameters, the primary hypothesis pointed to a localized hardware malfunction rather than a fundamental design flaw. In the presence of a localized hardware defect, the cavity bypassed the seeded mode-locked regime and lased freely at the natural emission peak of the Ytterbium-doped silica active medium (around 1030 nm), where the gain is highest. This parasitic CW operation saturated the active fiber gain, preventing the starting of the ML. To diagnose the root cause, the cavity was systematically dismantled to evaluate each component. Due to the severe risks associated with back-reflections, all APC fiber tips, specifically those on the coupler, the seeder, and the 10% tap port, were continuously inspected and cleaned. Any tip showing suspected surface damage or questionable physical integrity was immediately replaced to definitively rule out parasitic feedback. This diagnostic phase provided, also, an opportunity to investigate the intracavity power dynamics. Because the active fiber in the industrial prototype differed from the laboratory setup, and the instabilities consistently emerged only above the 70%-80% pump threshold, suspecting a fundamental energy imbalance alongside potential hardware defects was coherent. To test the hypothesis that an unoptimized circulating

power level was driving the instability, different output coupling ratios were evaluated by temporarily integrating a 50/50 coupler and reversing the ports of the existing 30/70 component.

Substituting the original damaged 2x2 coupler with a new PM 70/30 1x2 coupler completely eliminated the anomalous CW lasing at 1030 nm and the double-pulsing behavior. This confirmed that the initial 2x2 coupler had sustained localized internal thermal damage within its fused coupling region, which acted as a parasitic Fabry-Perot cavity that fundamentally disturbed the pulse evolution. Crucially, the transition to a 1x2 device (a 3-port configuration) eliminated the auxiliary diagnostic port on the input side, physically suppressing a primary source of parasitic back-reflections and localized insertion losses within the cavity. In this final layout, 70% of the power is directed to the main output, while 30% is dedicated to the cavity feedback. Meticulous fiber re-cleaving and fusion splicing to integrate the new 1x2 coupler slightly reduced the total physical length of the passive fibers, marginally shortening the cavity round-trip path and shifting the fundamental repetition rate from the initial 10.07 MHz to the final optimized value of 10.44 MHz. Following multiple successful starting tests, the engineered industrial MO prototype proved to be robust and stable. The complete comparative characterization between the initial unoptimized cavity and the final optimized configuration is illustrated in Figure 3.9.

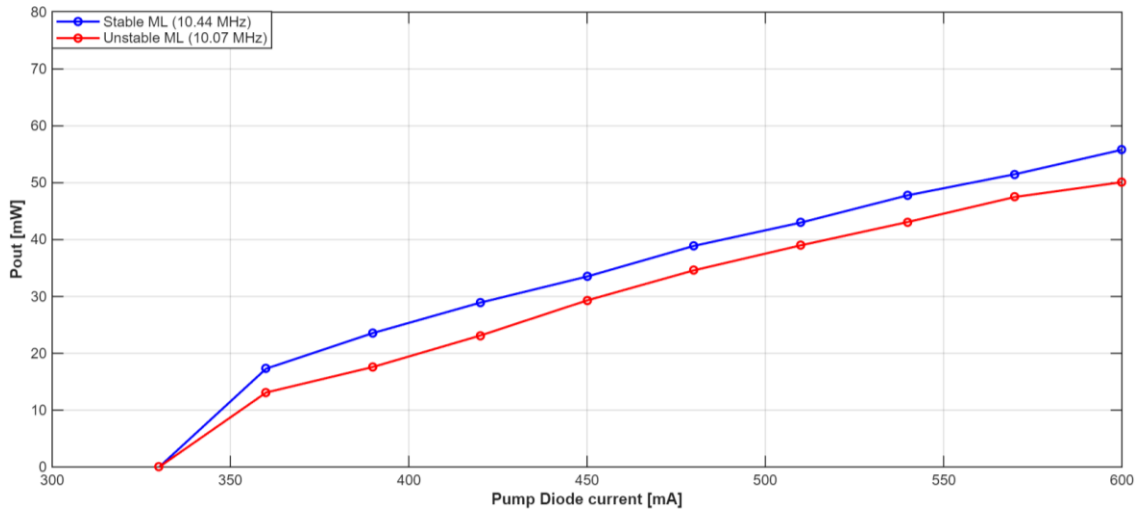


Figure 3.9 Measured output power of the industrial MO, in blue, the final stable cavity configuration operating at 10.44 MHz, in red, the unstable configuration at 10.07 MHz.

A slight but distinct increase in both the slope efficiency and the average output power can be observed with this last configuration. This performance enhancement is primarily attributed to the successful elimination of the parasitic continuous-wave lasing around 1030 nm, which was previously draining energy from the mode-locked signal, coupled with a general reduction of intracavity losses due to newly optimized fusion splices.

Furthermore, Figure 3.10 illustrates the evolution of the optical spectrum as a function of the pump diode driving current. As the current increases, represented by the orange (60%), red (~80%), and blue (95%) traces, the spectrum undergoes progressive and significant broadening. This behavior is driven by the increased intracavity peak power, which

enhances the SPM effect during propagation in the active and passive fibers. While operating the laser at even higher driving currents would theoretically yield an even wider spectrum, this operational regime must be avoided. Excessive spectral broadening and unconstrained peak power push the circulating pulses dangerously close to the SRS threshold and because this oscillator serves as the front-end for a MOPA architecture, maintaining a high spectral purity is critical. If the oscillator output approaches the Raman regime, it will introduce detrimental Stokes-shifted noise into the seed pulse. During the subsequent amplification stage, this would trigger Raman conversion, severely degrading the pulse quality and depleting the energy of the main signal.

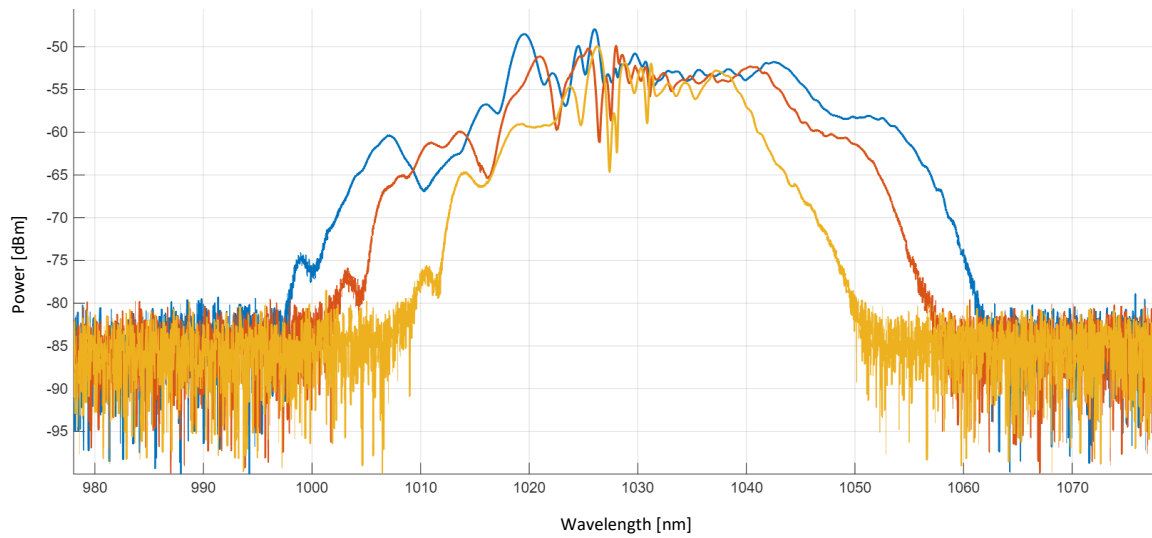


Figure 3.10 Output spectrum in logarithmic scale measured at different pump diode driving currents.

For this precise opto-mechanical reason, the final engineered oscillator is deliberately tuned to operate at a moderate driving current, avoiding the 100% capacity of the pump driver. This strategy ensures the delivery of a clean, stable, and Raman-free seed, providing the ideal starting condition for the subsequent power amplification section. Because the temporal dynamics of this specific cavity architecture had already been thoroughly characterized during the previous laboratory studies and given the temporary unavailability of an autocorrelator at the company's facility, dedicated pulse duration measurements were postponed. Confident in the established reliability of the oscillator's output, the experimental focus immediately shifted to the preliminary installation and integration phases of the subsequent amplification stage.

3.5 Implementation of the amplification stage

The integration of the amplification stage began with the installation of its dedicated high-power pump source. For this section, the system utilizes a high-power, multimode fiber-coupled LD (BWT K976AB2RN-9.000WN0N-10522B20ENA5). This module delivers a

maximum CW output power of 9 W through a 105 μm core fiber with a numerical aperture (NA) of 0.22. The emission is wavelength-stabilized at 976 nm via an integrated Volume Bragg Grating (VBG). This stabilization ensures a remarkably narrow spectral bandwidth (≤ 0.7 nm), which is ideal for maximizing the absorption cross-section of the Ytterbium-doped active fiber. Furthermore, to ensure long-term reliability in high-gain MOPA architecture, the diode package features built-in feedback protection, shielding the emitter from backward-propagating light in the 1020 nm to 1200 nm range.

Given the substantial optical power and the resulting thermal load generated by the 9 W diode, efficient heat dissipation is an absolute requirement to prevent performance degradation or catastrophic failure. Following standard opto-mechanical engineering practices, the diode was mounted directly onto a dedicated metallic heat sink. To maximize heat transfer and eliminate insulating air gaps, a uniform layer of thermal conductive paste was applied with a spatula to the bottom footprint of the package prior to rigidly securing it to the base. To effectively route this energy into the active medium, the pump source is spliced to a Polarization-Maintaining Forward Pump Combiner (Seagnol PMPSC-1040-111-F-10-125-PM98-10/125-10). This passive device combines the high pump radiation with the PM signal coming from the MO, coupling both into the LMA output fiber to drive the amplification stage. Figure 3.11 shows the measured output power characterized as a function of the driving current to evaluate the coupling efficiency of the amplification stage. The graph compares the LD emission (blue trace) with the optical power successfully transmitted through the forward pump combiner (red trace). Both curves exhibit the typical linear response expected above the emission threshold, ensuring stable and predictable power delivery. Based on these experimental measurements, the pump combiner demonstrates highly efficient power handling, yielding an average transmission of approximately 96% (corresponding to an insertion loss of only ~ 0.18 dB) across the entire operational range. This minimal loss guarantees that the vast majority of the pump energy is effectively routed into the LMA fiber to drive the active medium.

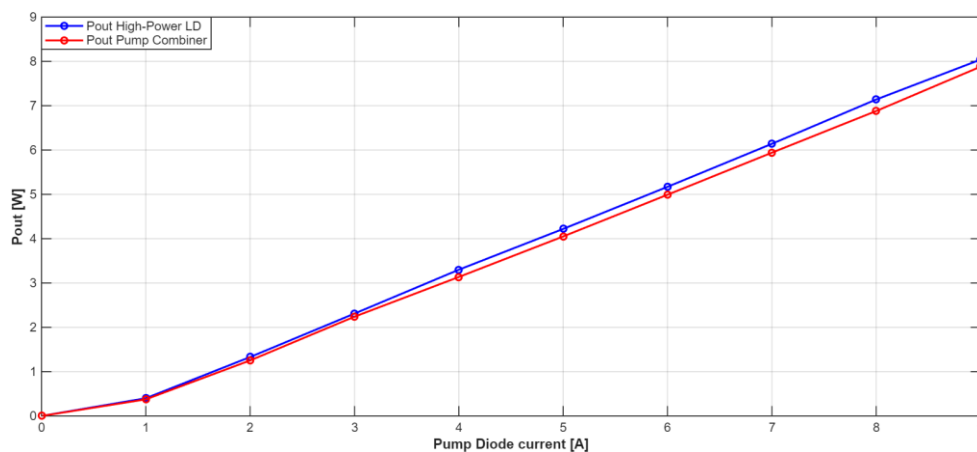


Figure 3.11 LD output power as a function of the driving current, in blue, and in red the output power measured after the combiner.

Returning to the output of the Master Oscillator, following the validation of the pump delivery line, an optical circulator was fusion-spliced to the signal output port. Specifically, Port 1 of the circulator was directly spliced to Port 3 of the 30/70 intracavity coupler. This passive component is critical within a MOPA architecture to optically isolate the oscillator, effectively preventing any amplified back-reflections or backward-propagating ASE from destabilizing the mode-locking regime or causing catastrophic damage to the front-end components.

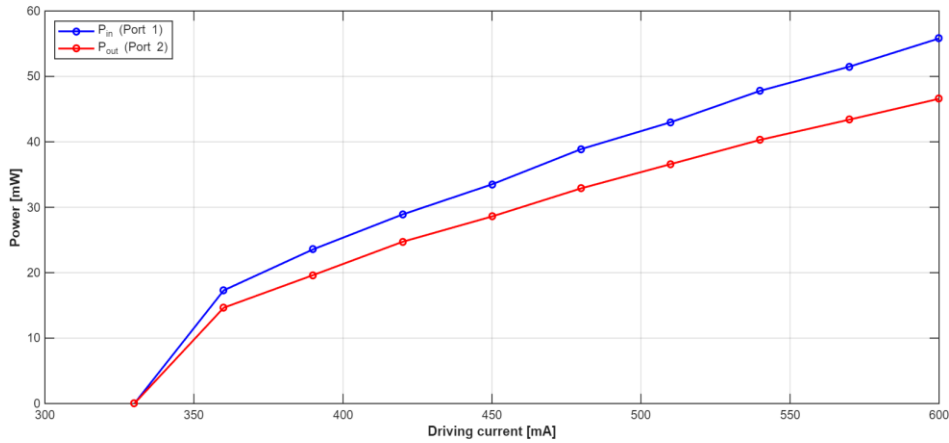


Figure 3.12 Output from the Port 2 of Circulator.

Once the splicing procedure was completed, the forward transmission of the circulator was characterized to quantify its insertion losses and verify that an adequate, well-calibrated seed power was delivered to the subsequent amplification stage. As shown in Figure 3.12, the optical power was measured before the circulator (Port 1 input, represented by the blue trace) and after it (Port 2 output, represented by the red trace). The experimental data yielded an average forward transmission of 84.5%, corresponding to an insertion loss of approximately 0.73 dB, which fully aligns with the nominal specifications for this class of devices. In the finalized MOPA layout, Port 2 of the circulator is fusion-spliced directly to a fiber MC. An engineering constraint during this specific assembly step is to minimize the fiber length between the circulator and the MC. This precaution is necessary to prevent the accumulation of uncompensated material dispersion and nonlinear phase shifts, thereby avoiding excessive temporal broadening of the pulse before it enters the free-space compressor. Upon exiting the micro-collimator, the free-space beam is directed toward a reflection grating, strategically positioned within the isolated protective housing adjacent to the MO grating. Following reflection, the retro-coupled signal is routed through Port 3 of the circulator directly to the PM input of the forward pump combiner. From there, the seed is injected into the LMA active fiber to undergo power amplification. To ensure the stability of the entire chain and suppress any parasitic back-reflections that could propagate backward through Port 2 into the oscillator, the output end of the active LMA fiber is angle-cleaved.

However, due to external supply chain delays that prevented the timely delivery of key optical components, most notably the high-efficiency compression grating, the physical integration and final testing of the amplification stage had to be postponed. Consequently, the physical assembly of the power amplifier, the spatial alignment of the compressor, and the subsequent high-power diagnostics are left for future implementation. Nevertheless, the theoretical, physical, and opto-mechanical layout of the final MOPA architecture has been completely defined and validated, as illustrated in the schematic in Figure 3.13. The conclusive results achieved on the front-end oscillator stage provide a robust, engineered foundation for the completion of this industrial-grade ultrafast laser source.

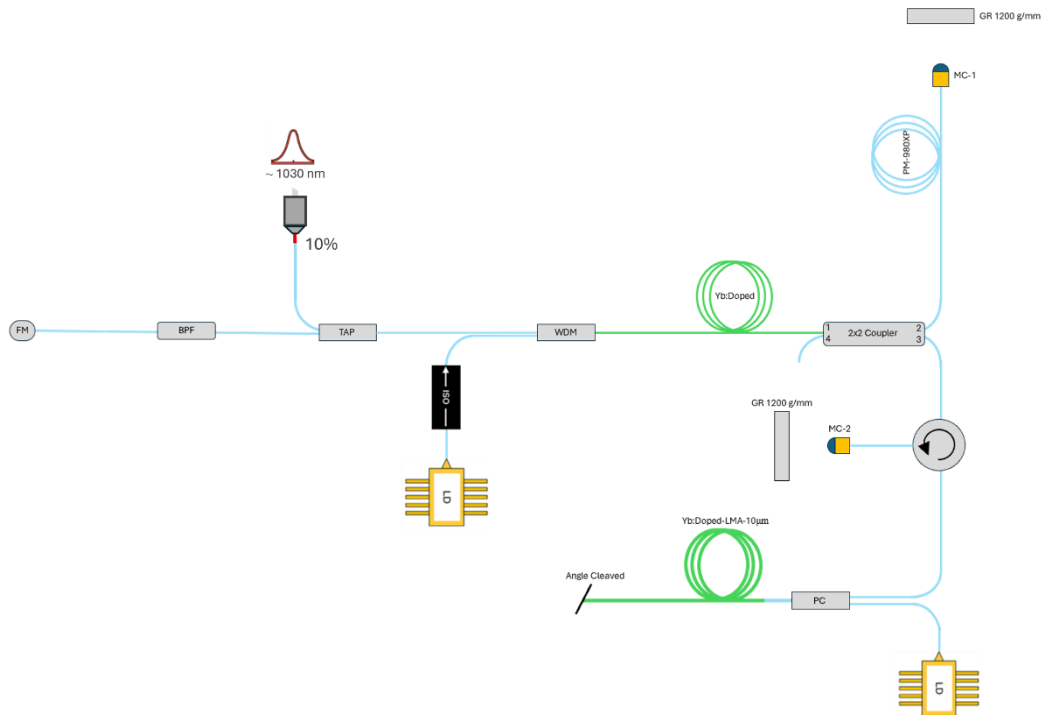


Figure 3.13 MOPA layout.

CONCLUSIONS

This Thesis has addressed the design, construction, and experimental validation of two distinct ultrafast Yb-doped fiber laser architectures for industrial-grade femtosecond pulse generation at 1030 nm, moving progressively from laboratory-scale demonstrations toward an engineered, cleanroom-assembled prototype. In the first part of this work, a SESAM-mode-locked dissipative soliton oscillator operating in the All-Normal Dispersion regime was investigated. An initial unidirectional ring cavity, inspired by literature designs, proved unstable due to a combination of circulator-induced parasitic effects and the intrinsic limitations of super-Gaussian spectral filtering. This finding motivated the transition to a linear, standing-wave architecture combining a fiber-coupled SESAM with Gaussian spectral filtering from a Littrow-mounted diffraction grating, which was shown both experimentally and numerically to provide a substantially broader and more stable mode-locking regime.

The optimized oscillator, seeding a Gain-Managed Nonlinear Amplification stage, successfully demonstrated multi-watt, sub-50-fs pulse generation, confirming the viability of the ANDi platform as a MOPA front-end. At the same time, this activity exposed the structural reliability limit of SESAM-based sources for industrial deployment: signs of thermally induced degradation over long-term operation emerged during the amplification experiments, likely linked to the absence of active cooling on the absorber combined with the relatively high output power levels required from the oscillator.

This limitation directly motivated the second and more extensive part of the Thesis: the development of a Mamyshev oscillator, whose virtual, damage-free saturable absorber mechanism removes the SESAM as a reliability bottleneck. Starting from the semi-integrated architecture validated at the Laser Sources Laboratory, an industrial prototype was engineered and physically assembled in the company's cleanroom, combining fiber-integrated components with a single free-space diffraction-grating arm to preserve wavelength tunability. A compact, all-fiber DFWM-based seeding stage, exploiting a low-cost passively Q-switched microchip laser, was redesigned, characterized, and integrated to reliably trigger mode-locking at the Ytterbium gain peak. Following the diagnosis and resolution of a hardware fault in the intracavity coupler, the prototype achieved robust, self-starting, and reproducible mode-locked operation at 10.44 MHz, delivering ~50 mW of average power with a ~20 nm spectral bandwidth, meeting the target specifications defined at the outset of the project.

The opto-mechanical and theoretical design of the subsequent GMNA power-amplification stage was also completed and validated, although its physical integration and characterization had to be postponed due to component supply-chain delays, and remain the natural next step of this development.

Beyond the technical results, this Thesis represented a significant learning experience for the candidate, who was directly involved in the transition of a laser source from a laboratory proof-of-concept to an industrially engineered device. This process required not only a solid grasp of nonlinear fiber optics and mode-locking dynamics, but also hands-on opto-mechanical assembly and fiber-splicing skills, rigorous experimental diagnostics under cleanroom conditions, and close day-to-day collaboration between the University and the company's engineering team, an experience that closely mirrors the translational challenges of real-world photonics product development.

Looking forward, the completion and characterization of the amplification and compression stage remains the immediate priority, together with pulse-duration measurements once autocorrelation equipment becomes available. On a longer timescale, scaling toward larger-core LMA fibers will be needed to push the achievable pulse energy while staying below the Stimulated Raman Scattering threshold, and further environmental sealing and packaging refinement will be required to bring long-term stability in line with industrial reliability standards. Taken together, the results obtained on the oscillator front-end provide a solid and validated foundation for the completion of a fully industrial-grade ultrafast laser source.

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