

Development of a space-grade chirped pulse amplifier for GHz-class optical frequency combs

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ABSTRACT

We present a chirped pulse amplification architecture optimized for GHz-class optical frequency combs. High repetition rate pulsed lasers are inherently limited by nonlinear distortion and gain saturation during amplification. Chirped pulse amplification is used to prepare femtosecond pulses for semiconductor optical amplifiers, enabling efficient optical energy extraction. To optimize pulse quality at GHz repetition rates, we present an amplifier design that combines an extended bandwidth chirped Bragg grating with minimized fiber propagation lengths. This approach reduces pulse distortion and chirp due to accumulated phase delay, providing a pulse energy of 99 pJ and an amplification of 12.3 dB suitable for super continuum generation and operation of an f-2f-interferometer.

Keywords: Chirped Pulse Amplification (CPA), Chirped Volume Bragg Grating (CVBG), Optical Frequency Comb (OFC), Diode-Pumped Solid-State Laser (DPSSL), Kerr-lens modelocking, Supercontinuum Generation, Nonlinear Optics

1. INTRODUCTION

Femtosecond lasers are a key technology for next-generation space clocks and frequency referencing applications. In optical clocks, they provide the means of down-conversion of optical frequencies to the microwave domain, enabling the accessibility of the optical signals at microwave frequencies while preserving unprecedented phase coherence, frequency resolution and stability¹. Furthermore, optical frequency combs (OFC) provide the foundation for laser-based links within space-borne interferometric constellations.

Scaling space-qualifiable frequency combs from the MHz into the GHz regime offers the operational advantages of an inherently small footprint, improved mode accessibility and higher power in individual comb modes, yielding reduced measurement acquisition time and improved signal-to-noise ratio (SNR). However, those systems suffer low pulse energies and peak powers, limiting their ability to drive the nonlinear processes in a self-referenced OFC (i.e., supercontinuum generation (SCG)). To overcome these limitations, the laser signal needs to be amplified.

One commonly used approach for amplification is the chirped pulse amplification (CPA) technique². In this method, pulses are temporally stretched before amplification, which decreases the peak power in the amplifier. This reduction mitigates nonlinear effects and gain saturation, enabling high-energy amplification with reduced amplified spontaneous emission (ASE). In this work, we present an optimized CPA architecture specifically designed for GHz-class laser operation. By employing a broadband chirped volume Bragg grating (CVBG) and minimizing the fiber length of the fiber-coupled amplifier, we demonstrate low spectral distortions with reasonable amplification at high repetition rate.

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2. THEORETICAL BACKGROUND

2.1 Nonlinearities in Semiconductor Optical Amplifiers

Semiconductor optical amplifiers (SOAs) are highly attractive for high-bandwidth pulse amplification due to their high gain, compact footprint, and excellent beam quality when fiber-coupled. However, the amplification of ultrashort pulses is fundamentally constrained by several nonlinear and dynamical effects such as self-phase modulation (SPM)³. When the pulse duration is significantly shorter than the carrier recombination lifetime of the semiconductor, the gain dynamics become non-instantaneous^{3,4}. Gain saturation causes carrier intensity variations and thus refractive index changes. The leading edge of the pulse extracts a disproportionate amount of energy from the population inversion. Consequently, the trailing edge of the pulse experiences a reduced gain, resulting in temporal pulse asymmetry and spectral distortions⁵. Pulse durations of tens of ps and less are associated with carrier heating and spectral hole burning⁴. Additionally, the maximum achievable output energy saturates at a lower level for shorter fs-pulses than for ps-pulses⁶. Furthermore, during the intervals between successive pulses, ASE accumulates⁷, which degrades the SNR and overall signal quality. At excessive peak powers, these effects might even lead to permanent optical damage to the gain medium.

Fiber-coupled SOAs introduce additional challenges arising from the fiber passage. In addition to chromatic dispersion, the strong transverse mode confinement within the fiber enhances the effective intensity for the pulse's high peak powers and thereby intensifying nonlinear optical effects. The refractive index of the medium becomes intensity-dependent, described by the nonlinear refractive index n_2 :

$$n(I) = n_0 + n_2 \cdot I(t) \quad (1)$$

This leads to SPM, which induces a nonlinear phase shift and spectral broadening. A critical complication arises because the resulting phase is intensity-dependent and thus nonlinear, and cannot be compensated for entirely by conventional linear dispersion compensation elements (e.g., gratings or prisms). This might lead to residual chirp and degraded pulse quality after compression. Such parasitic phase distortions influence nonlinear processes, such as SCG, by inducing spectral instabilities and reducing the coherence of the generated continuum.

2.2 Chirped Pulse Amplification

To mitigate these nonlinearities, the CPA technique² is employed. The core principle of CPA is to temporally stretch the pulse before amplification, thereby reducing the peak power while preserving the total pulse energy. By increasing the pulse duration $\Delta\tau_{pulse}$, the peak power $P_{peak} \sim \frac{E}{\Delta\tau_{pulse}}$ is lowered to a level where the medium operates in a quasi-continuous-wave regime. This suppresses both gain saturation in the SOA and SPM in the fiber-coupling stages. After amplification, the stretched pulse is recompressed to its transform-limited duration using a dispersion-compensating element. As illustrated in Figure 1, the process follows a sequence of stretching, amplification, and recompression. This work uses as chirped volume Bragg grating (CVBG) for both stretching and recompression.

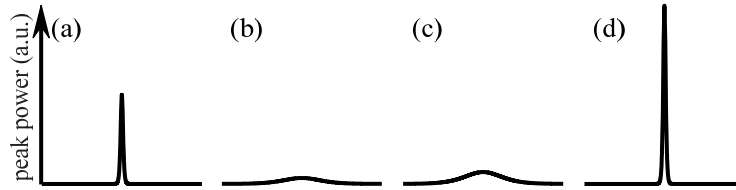


Figure 1. Evolution of pulse length and peak power in a CPA. (a) Pulse to be amplified, (b) unamplified stretched pulse, (c) amplified stretched pulse, (d) amplified, recompressed pulse.

A volume Bragg grating (VBG) consists of a periodic refractive index modulation inscribed within a bulk medium. The fundamental resonance occurs at the Bragg wavelength λ_B , which satisfies the Bragg condition:

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda \quad (2)$$

where n_{eff} is the effective refractive index of the medium and Λ is the grating period. In a CVBG, the grating period Λ is spatially varied along the longitudinal axis of the material. This spatial chirp introduces a strong frequency-dependent

group delay, making the CVBG a highly dispersive element. The dispersion provided by the CVBG can be characterized by the group delay dispersion (GDD). By tailoring the spatial variation of $\Lambda(z)$, the GDD can be precisely engineered to match the required stretching or compression profiles.

Figure 2 depicts the process. When an ultrashort pulse enters the "blue end" of the CVBG, the different spectral components of the pulses are reflected at different longitudinal positions, referred to as grating planes, depending on their wavelength. This results in a significant temporal stretching of the pulse since high-frequency components (blue) are reflected earlier in the medium compared to low-frequency components (red).

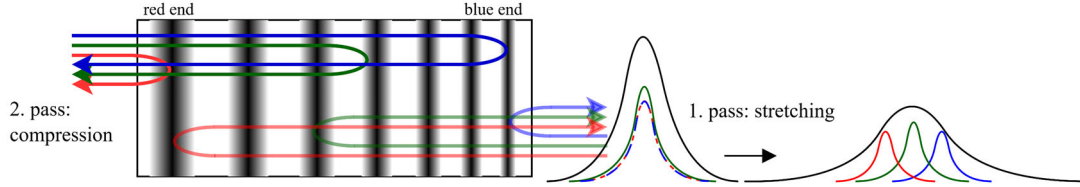


Figure 2. Schematic of CVBG used as a highly dispersive medium for symmetric pulse stretching and pulse compression.

A significant advantage of this approach is the ability to tailor the CVBG specifically for a target central wavelength, a broad operational bandwidth, and a customized dispersion profile. This allows for a highly optimized match between the dispersion, the required pulse duration, and the laser's repetition frequency. Furthermore, the CVBG serves a dual purpose in our architecture: it acts as both a stretcher and a compressor. Following the amplification stage, the pulses enter the CVBG from the opposite side (the "red end"), allowing for symmetric recompression of the pulses to their near-transform-limited duration, as schematically shown in Figure 2.

The use of CVBGs for pulse stretching has been demonstrated for ultrashort pulses in the GHz domain^{8,9}. While Ostapenko et al. utilized a similar central wavelength of 1076 nm and a repetition rate of 2.2 GHz, they observed several performance constraints. Specifically, the CVBG bandwidth was insufficient to support the full spectrum, resulting in a distorted pulse shape with a duration-bandwidth product of 0.5, compared to the transform-limited 0.315 for a sech^2 -shaped pulse before amplification. Furthermore, uncompensated GDD within the SOA fibers reduced the peak power. The present work addresses these issues through an optimized design featuring an expanded CVBG bandwidth and a reduced fiber length to preserve the sech^2 pulse shape, maximize the peak power and minimize cumulative nonlinearities.

3. EXPERIMENTAL SETUP

3.1 GHz class Kerr-Lens Modelocked Laser

To overcome the limitations of existing spaceborne Er:fiber frequency combs, such as low repetition rates, extended physical footprints, and susceptibility to radiation-induced degradation¹⁰, this work employs a diode-pumped solid-state (DPSS) mode-locked laser architecture. The underlying self-starting, bonded Kerr-lens mode-locked (KLM) laser system was previously described and presented in detail at ICSO 2020¹¹.

The laser operates at a high repetition rate of 1.5 GHz, providing a compact platform with dimensions of $177 \times 50 \text{ mm}^2$. It emits near-bandwidth-limited pulses with a duration of 172 fs, a central wavelength of 1078 nm, and a spectral bandwidth of 8.6 nm. By utilizing KLM, the system benefits from inherently lower phase noise compared to conventional fiber-based architectures. Furthermore, the use of a compact crystalline gain medium instead of long fiber significantly reduces sensitivity to radiation which is a fundamental short-coming of fiber-based combs despite years of investigation^{12,13}. The 2% Yb-doped Y_2O_3 crystal is placed at Brewster's angle to implement a low-loss bow-tie ring cavity (Figure 3). To enable precise repetition rate tuning, one cavity mirror is mounted on a piezoelectric transducer, allowing for a f_{rep} tuning range of 15.7 kHz, corresponding to a 2.9 GHz shift near the peak wavelength, equivalent to an offset tuning of almost two comb modes.

To mitigate the typical challenges of solid-state lasers, such as reduced mechanical long-term stability and sensitivity to environmental fluctuations¹⁴, a semi-monolithic design was implemented. As described by Lamour et al.¹¹ and Feng et al.¹⁵, the 4 mm optics are adhesively bonded to minimize thermal and micro-vibration-induced noise, achieving an integrated phase noise of 3.0 mrad (1 Hz–1 MHz) during active stabilization¹⁵.

Despite these advantages, the output pulse energy of high repetition rate lasers is intrinsically limited by the availability of high power, high beam quality pump diodes. Consequently, the pulse energies are insufficient to drive high-order nonlinear processes, necessitating the subsequent amplification stage presented in here.

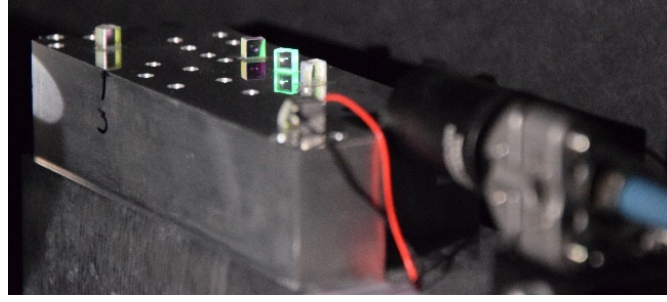


Figure 3. Semi-monolithic KLM laser in bow-tie ring cavity configuration on its solid Al-baseplate.

3.2 Amplification stage

The experimental configuration, based on the architecture described in Sakamoto et al.⁹, is illustrated in Figure 4. The system is designed to stretch, amplify, and recompress ultrashort pulses using a polarization-controlled optical path.

The laser signal is initially directed through a half-wave plate (HWP) to set the required input polarization to be transmitted through a polarizing beamsplitter (PBS). The light then passes through a quarter-wave plate (QWP), which converts the linear polarization into circular polarization. The pulse enters the CVBG via the “blue end”, initiating the temporal stretching process. After spectral selective reflection in the grating, the polarization is re-linearized by the QWP and the light is now reflected at the PBS toward the fiber-coupled SOA. After amplification, the pulse follows the same polarization logic in reverse to enter the CVBG now from the "red end" to undergo symmetric recompression. To minimize nonlinearities and dispersion-induced distortions, the fiber lengths on both the input and output sides of the SOA were reduced to about 20 cm per pigtail.

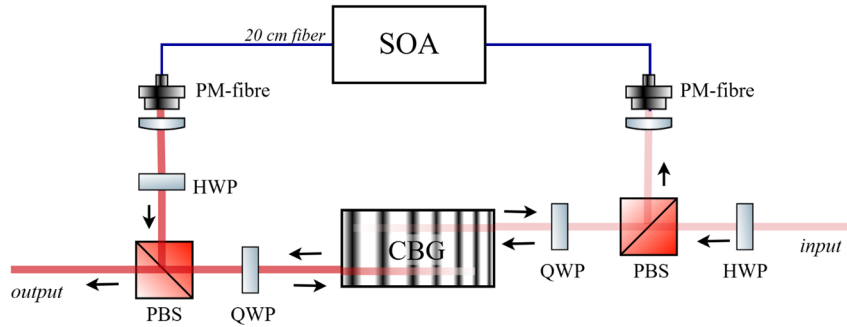


Figure 4. Schematic of the CPA. The right half is showing the stretching of the pulses while the left half is showing the re-compression after the amplification.

The amplification stage utilizes a SOA from Innolume GmbH (model SOA-1080-20-PM-40dB), specifically selected to match the central wavelength of the oscillator. The CVBG, manufactured by Optigrade USA, is composed of PTR glass, a material characterized by an unrestricted lifetime, low absorption coefficients, and high stability in harsh environments¹⁶. The CVBG has a total length of 72 mm, optimized for a central wavelength of 1078 nm. The grating provides a spectral bandwidth of 25.7 nm and a chirp rate, expressed as time-delay dispersion, of 26 ps/nm. The stretching capability of the CVBG extends the pulse duration to approximately 670 ps. This duration is carefully matched to the laser's repetition period of $T_{rep} = 1/f_{rep} \sim 660$ ps. To maintain high pulse quality, the grating bandwidth must be significantly larger than the pulse bandwidth; specifically, it should be at least twice the Full Width at Half Maximum (FWHM) of the laser spectrum¹⁷. Given the oscillator's bandwidth of 8.6 nm, the 25.7 nm bandwidth of the CVBG provides sufficient margin, resulting in a spectral clipping loss of less than 1.5% of the total pulse energy. Furthermore, the extreme stretching

significantly mitigates nonlinear effects. For a transform-limited pulse of 140 fs, the stretching to 670 ps reduces the peak power by more than 99.9%, thereby ensuring the system operates in a regime where nonlinear phase shifts are minimized.

4. CHARACTERISATION, RESULTS AND DISCUSSION

4.1 Oscillator Characteristics and Pulse Characterization

The performance of the amplification stage is predicated on the stability and spectral properties of the seed oscillator. For all subsequent measurements, the oscillator was operated in a unidirectional mode in the forward direction (relative to the pump direction), delivering a total output power of 8.85 mW with a spectral 3-dB bandwidth of 8.6 nm.

To characterize the temporal profile of the seed pulses, interferometric intensity autocorrelation (AC) was performed using a 1 mm thick BBO crystal. The data analysis and fitting of the AC curves were based on a sech^2 pulse shape, constrained by the measured optical spectrum. Second- and third-order dispersion parameters were adjusted to achieve a high-quality fit, allowing for the accurate derivation of the pulse duration. The results, illustrated in Fig. 5, indicate that the seed oscillator's pulses are bandwidth-limited sech^2 pulses with a duration of 172 fs. To achieve an optimal fit, a GDD of 3800 fs^2 was employed, which deviates from the calculated value of 400 fs^2 for the employed optics for the AC measurement. The specific fit parameters used are summarized in Table 1, row one. Based on the derived temporal profile, the pulses exhibit a peak power of 29.9 W and a pulse energy of 5.8 pJ. For comparison, a transform-limited sech^2 pulse with a bandwidth of 8.6 nm would correspond to a duration of 142 fs.

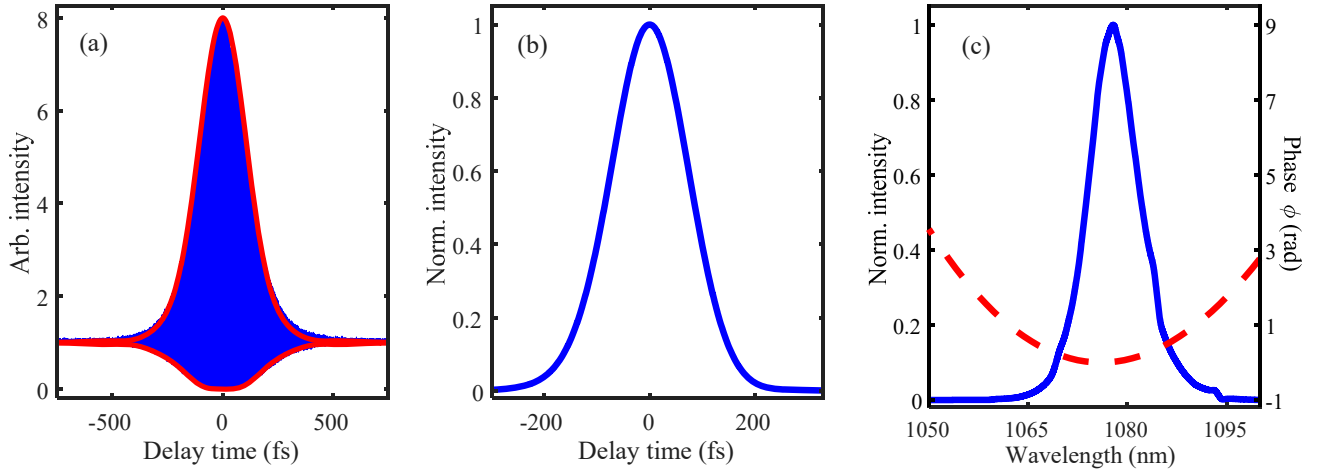


Figure 5. Measured interferometric intensity AC signal of cavity output at 8.85 mW and 8.6 nm FWHM with a pulse duration of 172 fs. (a) Fitted AC trace (red) with added dispersion and measurement data (blue), (b) Derived pulse shape and (c) Optical spectrum (blue) and phase (red).

Table 1. Specification of seed oscillator and amplification performance.

	Spectrum		Power			Fitted Pulse Parameters		
	Peak wavelength [nm]	FWHM [nm]	Average [mW]	Energy [pJ]	Peak [W] (sech^2)	Fitted duration [fs]	GDD [fs^2]	TOD [fs^3]
Cavity	1077.8	8.6	8.85	5.86	29.9	172	3784	-28
Amplified at 400 mA	1072.9	11.5	75.8	50.2	181.0	244	19239	-4444616
Amplified at 800 mA	1075.5	12.6	150	99.3	393.9	237	13521	-4377606

4.2 Amplification Performance

The amplification was evaluated by measuring the output power as a function of the SOA pump current (Figure 6 (a)). To ensure the stability of the mode-locking process, the system was optimized to suppress back-reflections from the SOA into the oscillator cavity. High pump currents were found to induce parasitic reflections that perturbed the oscillator's stability. Consequently, an optical isolator (Thorlabs IO-3D-1064-VLP) was integrated into the setup. While this addition introduces a small amount of additional dispersion and losses, it enables stable output powers at elevated SOA pumping. A stable operating point was selected at a pump current of 800 mA, yielding an average output power of 150 mW.

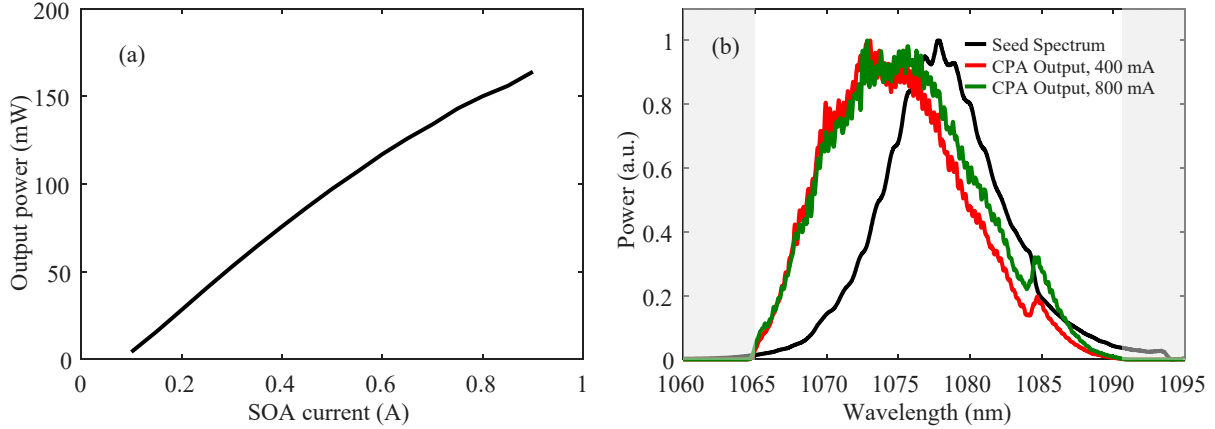


Figure 6. (a) Total CPA output power for given SOA current at constant seed power (b) Linear spectra before and after amplification at a resolution bandwidth of 0.1 nm, with grey-shaded regions indicating wavelength bands outside the CBG bandwidth.

The spectral evolution during the amplification process is presented in Figure 6 (b), showing the input seed spectrum and the CPA output spectra. Due to the large CVBG bandwidth, the spectral clipping is minimized and the power loss is less than 1.5 % of the pulses' total power. The gray-shaded regions in the plot indicate the wavelength ranges that fall outside the reflection bandwidth of the CVBG and are cut off. While the seed peak wavelength was located at 1077.8 nm, a blue shift of 4.9 nm to a peak wavelength of 1072.9 nm is observed for the amplified signal at a pump current of 400 mA. This spectral shift is attributed to the gain dynamics of the SOA. At 800 mA pump current, the SOA enters the saturation regime, the blue shift is partially compensated, leading to a peak wavelength at 1075.5 nm and a blue shift of 2.3 nm. This amplification nonlinearity also increases the spectral bandwidth from 8.6 nm (cavity) to 11.1 nm at 400 mA and up to 12.5 nm at 800 mA pump current.

The temporal characteristics of the amplified pulses were characterized using the same AC setup employed for the cavity pulses, the corresponding fit parameters are summarized in Table 1, row two and three. Prior to measurement, the cumulative uncompensated GDD for all primary optical components was calculated to be approximately 27500 fs². This dispersion profile is dominated by the SOA and its fiber pigtails, which account for over 75% of the total cumulative chirp. The remaining dispersion is primarily contributed by the CVBG and the isolator, playing a secondary role in the overall dispersion budget. Based on an initial sech² pulse of 172 fs, a pulse stretching to 360 fs was theoretically expected. In contrast, experimental measurements for SOA pump currents of 400 mA (Fig. 7) and 800 mA (Fig. 8) yielded pulse durations of 244 fs and 237 fs, respectively. The GDD values used in the fits, 19200 fs² and 13500 fs², are consistent with the calculated theoretical values. Furthermore, both amplified signals were fitted with a negative third-order dispersion (TOD) on the order of $-4 \cdot 10^7$ fs³. The measured pulse shapes exhibit oscillations and deviate from a sech² profile. While shorter pulse lengths are ideal for nonlinear processes, the mechanism responsible for the pulse compression requires further investigation. Even though the CVBG induces a slight spectral clipping, the observed temporal behavior is potentially driven by the interplay between the pulse bandwidth and the SOA's nonlinear gain profile or SPM.

The amplification stage successfully delivers pulses with a measured duration of approximately 240 fs and an average power of 150 mW, resulting in a peak power of 393 W. This represents a nearly thirteenfold increase compared to the seed oscillator's peak power of 30 W. Furthermore, theoretical calculations suggest that the implementation of an additional

recompression stage could further enhance the peak power to approximately 508 W. This increase in peak power is a critical prerequisite for driving efficiently subsequent nonlinear optical processes, specifically providing the necessary intensity threshold for high-quality SCG which is in turn the key enabler for the ultimate realization of a f-to-2f interferometer.

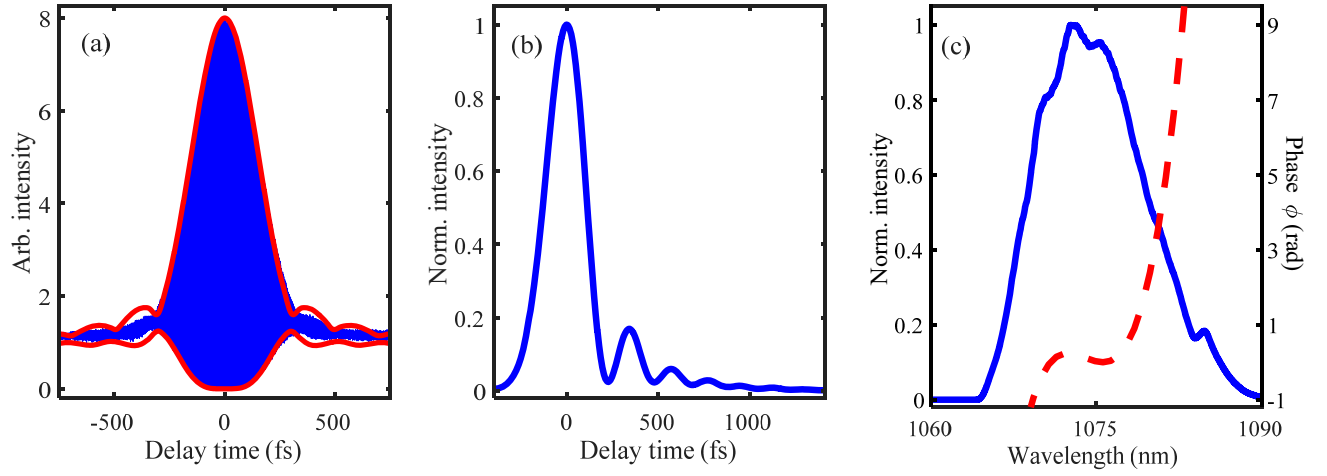


Figure 7. CPA at 400 mA SOA current: (a) Fitted AC trace (red) with added dispersion and measurement data (blue), (b) Derived pulse shape and (c) Optical spectrum (blue) and phase (red).

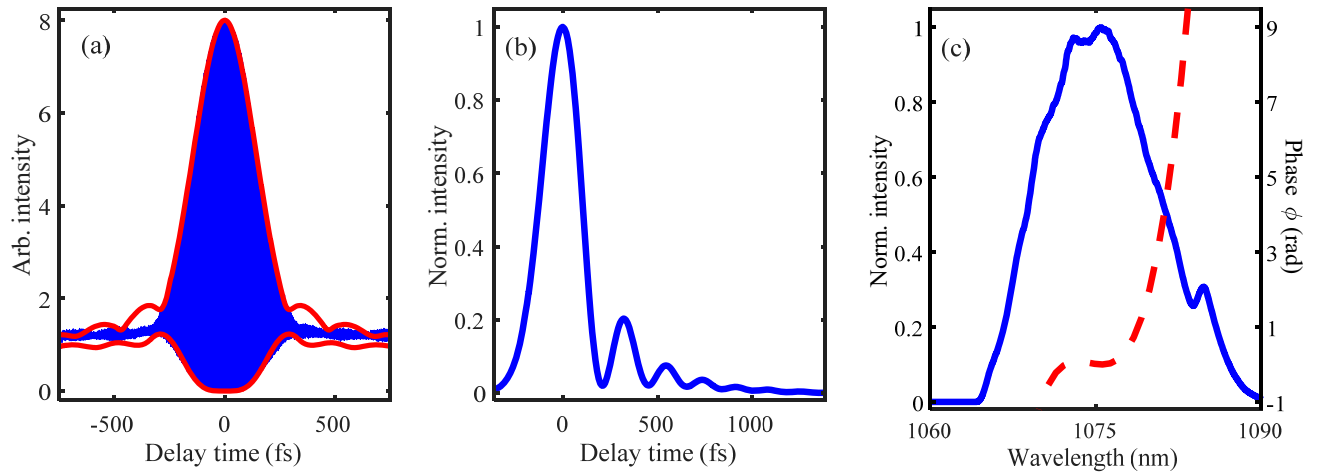


Figure 8. CPA at 800 mA SOA current: (a) Fitted AC trace (red) with added dispersion and measurement data (blue), (b) Derived pulse shape and (c) Optical spectrum and phase.

5. CONCLUSION AND OUTLOOK

In this work, a CPA system based on a CVBG and a SOA was successfully developed and characterized. The system demonstrates a significant amplification of seed pulses from an GHz-repetition-rate-oscillator, increasing the peak power from 30 W to 393 W at an average output power of 150 mW.

The spectral analysis revealed that the amplification process is accompanied by a blue shift and a spectral broadening from 8.6 nm to 12.5 nm which can be attributed to the nonlinear gain dynamics and saturation effects within the SOA. Selection of a fitted SOA gain profile with a matching wavelength peak could mitigate this. While the CVBG provides effective spectral filtering, the overall dispersion budget is dominated by the SOA and its fiber pigtails, accounting for over 75% of

the total added chirp. The integration of an optical isolator proved essential for maintaining oscillator stability against back-reflections, despite the introduction of additional dispersion. These results demonstrate that the SOA-based CPA stage provides a robust platform for high-peak-power pulse generation.

The successful demonstration of this SOA-based CPA architecture provides a critical proof-of-concept for high-power pulse amplification for GHz repetition rate lasers. This paves the way for the development of space-compatible, self-referenced OFCs, where high peak powers and robust amplification are essential for reliable comb stabilization.

To transition this technology toward space-readiness, several key developments are envisioned. After the successful proof-of-concept in the laboratory, further miniaturization and an integration strategy are required, based on the successful bonding approach used in the oscillator. In this context, a transition toward a free-space amplifier architecture could be explored to further reduce the footprint and minimize fiber-related GDD. It is noteworthy that despite the significantly reduced fiber lengths in the presented design, the SOA amplification medium itself contributes approximately half of the total dispersion currently provided by the SOA-fiber assembly. Therefore, a compression stage will be required in future amplifier designs to fully exploit the increased pulse energy for highest peak powers. The efficient nonlinear processes driven by such amplifiers, ultimately will enable the generation of a broad and stable supercontinuum for frequency comb applications in space-borne instruments.

ACKNOWLEDGEMENTS

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