External cavity multiwavelength semiconductor mode-locked lasers gain dynamics

1-1-2006

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**Recommended Citation**

Archundia, Luis C. and Delfyett, Peter J., "External cavity multiwavelength semiconductor mode-locked lasers gain dynamics" (2006).  
*Faculty Bibliography 2000s*, 5913.  
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Abstract: The gain dynamics of a semiconductor optical amplifier (SOA) were measured using pump-probe techniques for the amplification of 750 fs pulses, 6.5 ps pulses and multiwavelength pulses, obtained from an external cavity semiconductor mode-locked laser. Furthermore, the intracavity gain dynamics of an external cavity semiconductor mode-locked laser was measured under multiwavelength operation. The experimental results show how the inherent chirp in pulses from external cavity semiconductor mode-locked lasers result in a slow gain depletion without significant fast gain dynamics. This mitigates gain competition between wavelength channels and nonlinearities in the gain media (SOA), enabling the multiwavelength operation of external cavity semiconductor mode-locked lasers. Numerical simulations support the experimental results.

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OCIS codes: (140.4050) Mode-locked lasers; (140.5960) Semiconductor lasers; (190.5970) Semiconductor nonlinear optics including MQW; (250.5980) Semiconductor optical amplifiers

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1. Introduction

Time division multiplexing (TDM) and wavelength division multiplexing (WDM) are
techniques used to exploit the information transmission capabilities of optical fiber
communication systems, reaching terabits per second transmission rates [1-3]. The availability
of compact, reliable and cost effective multiwavelength pulse sources is of great importance
for these systems. Light from superluminescent diodes [4], spontaneous emission from fiber
amplifiers [5], supercontinuum generation from fiber [6], and femtosecond lasers [1, 7], are
examples of sources that have been spectrally sliced to be used as multiwavelength sources.
An alternative to spectrally sliced sources is the use of multiwavelength lasers, where multiple
wavelength channels are obtained directly from the laser. External cavity semiconductor
mode-locked lasers have been configured as multiwavelength lasers, and have proven to be
attractive candidates for TDM and WDM applications [8-11]. Up to 168 wavelength channels
at 6 GHz, yielding an aggregate pulse rate of 1 THz, have been obtained from a single
semiconductor laser [11].

To better understand the mechanisms that support multiwavelength operation of external
cavity semiconductor mode-locked lasers, pump-probe techniques were used to measure the
gain dynamics of a semiconductor optical amplifier (SOA) under multiwavelength pulse
amplification and the intracavity gain dynamics of an external cavity semiconductor mode-
locked laser under multiwavelength operation.

Carrier heating, carrier cooling, four wave mixing, and cross-phase modulation effects
were observed when the SOA gain dynamics were measured under multiwavelength pulse
amplification. These nonlinear effects are evident when amplifying dispersion compensated
pulses, and it is shown how these effects decrease when the amplified pulses contain the chirp
from the semiconductor mode-locked laser used as the pulse source. The pulse chirp broadens
the composite pulse, resulting in a slow gain depletion and in a reduction of the nonlinear
effects in the SOA.

The measurements of the intracavity gain dynamics of the external cavity semiconductor
mode-locked laser under multiwavelength operation revealed a temporal skew between pulses
corresponding to different wavelength channels and a slow gain depletion of the gain media,
avoiding carrier heating, carrier cooling and self-phase modulation effects. The slow gain
dynamics and a transient unsaturated gain prevent gain competition between wavelength
channels and enable multiwavelength operation.

Results from numerical simulations using a simple approach are presented supporting the
experimental results.

2. External cavity semiconductor mode-locked lasers

External cavity semiconductor mode locked lasers employ a semiconductor optical amplifier
(SOA) as the gain media [12]. A basic external cavity semiconductor mode-locked laser
includes a SOA, a back mirror and an output coupler. Lenses are used to collimate the light
emitted by the SOA and to focus it on the back mirror and the output coupler to increase the
cavity stability. Figure 1 shows a diagram of a basic external cavity semiconductor laser. The
laser can be actively mode-locked by biasing the SOA with a modulated current or passively
mode-locked by substituting the back mirror for a saturable absorber mirror (SA) and DC
biasing the SOA [13]. Active mode-locking is more stable than passive mode-locking due to the modulation of the bias current, but passive mode-locking yields pulses with a predominantly linear chirp, which can be compensated resulting in sub-picosecond pulses. Combining both mode-locking techniques, the laser can be hybridly mode-locked, where a saturable absorber is used as the mode-locker and the SOA is biased with a modulated current to add stability [14].

![Diagram of a basic external cavity semiconductor mode-locked laser.](image)

Fig. 1. Basic external cavity semiconductor mode-locked laser.

When the laser is mode-locked, the intracavity pulse is amplified, depleting the SOA gain, and when the amplified pulse reach the SA, the pulse leading edge is absorbed, bleaching the SA, allowing the remaining portion of the pulse to be reflected. The combination of the SOA gain depletion and the saturable absorber bleaching opens a time window that allows the pulse formation [13]. By the time the intracavity pulse complete a cavity round trip, the SOA gain has recovered and the SA has returned to its unbleached state. Pulses from external cavity hybrid semiconductor mode-locked lasers are typically longer than 5 ps with a predominant linear chirp and a time-bandwidth product several times the Fourier transform limit. These pulses can be compressed by linear dispersion compensation obtaining sub-picosecond pulses. Pulses shorter than 200 fs have been obtained from external cavity semiconductor mode-locked lasers after dispersion compensation [15].

A typical spectrum and autocorrelation of pulses from an external cavity semiconductor hybrid mode-locked laser are shown in Fig. 2. Figure 2(b) shows the autocorrelation of the pulses directly from the laser and after linear dispersion compensation using a dual grating double pass dispersion compensator [16].

![Graphs showing typical external cavity semiconductor hybrid mode-locked laser pulse spectrum (a) and pulse autocorrelations before (—) and after (---) dispersion compensation (b).](image)

Fig. 2. Typical external cavity semiconductor hybrid mode-locked laser pulse spectrum (a) and pulse autocorrelations before (—) and after (---) dispersion compensation (b).

Several nonlinearities can be observed when pulses are amplified in a SOA depending on the duration of the amplified pulses [17]. The main nonlinearities observed in external cavity semiconductor mode-locked lasers are self-phase modulation and carrier heating and carrier cooling effects [14]. Semiconductor gain dynamics occurring in a femtosecond time scale such as spectral hole burning and instantaneous nonlinearities, are fast compared with the time duration of the pulses from external cavity semiconductor mode-locked lasers, and are not considered in this work.
The index of refraction in semiconductors is strongly coupled to the gain ($n \propto -\text{gain}$). When pulses are amplified in a SOA, the induced time varying gain leads to a time varying index of refraction modulating the temporal phase of the amplified pulses resulting in an instantaneous frequency proportional to the negative derivative of the index of refraction with respect to time ($\omega_{\text{inst}}(t) \propto -\partial n(t)/\partial t$) [18]. If long pulses are amplified in a SOA, the pulses slowly deplete the gain, increase the index of refraction and modulate the pulse temporal phase, resulting in an instantaneous frequency shifted to low frequencies. We define a long pulse as one with a temporal duration longer than the SOA carrier cooling time (approximately one to two picoseconds). If pulses shorter than the SOA carrier cooling time are amplified, an additional ultrafast gain reduction associated with carrier heating is observed. As the hot carriers cool back to equilibrium, the gain partially recovers. This fast gain recovery results in an instantaneous frequency shifted to high frequencies. As a result, for the amplification of pulses shorter than the SOA carrier cooling time, the instantaneous frequency moves from low frequencies to high frequencies as the short pulses are amplified. Figure 3 summarizes the self-phase modulation effects in SOAs for the amplification of pulses longer and shorter than the carrier cooling time constant. This figure also shows the theoretical self-phase modulation effects for the amplification of a burst of short pulses in a SOA.

![Figure 3. Self-phase modulation effects in SOAs for the amplification of pulses longer and shorter than the SOA carrier cooling time and a burst of short pulses.](image)

Figure 4 shows experimental results for the amplification of linearly up chirped pulses of approximately 6.5 ps obtained from an external cavity semiconductor mode-locked laser, and Fig. 5 shows experimental results for the amplification of 750 fs pulses obtained by compensating the linear dispersion of the 6.5 ps pulses. Figures 4(a) and 4(b) show the spectrum of the 6.5 ps up chirped pulses before and after amplification. The enhancement on the long wavelength side of the spectrum after amplification is a result of the combination of the SOA gain and an instantaneous frequency shifted to low frequencies associated with the gain depletion as explained above. Figure 4(c) plots the pulse autocorrelation before and after amplification showing no significant pulse distortion introduced by the amplification process. Figure 4(d) represents the temporally resolved SOA gain measured by standard pump-probe techniques using 750 fs pulses as the probe pulses.
The experimental results for the amplification of the 750 fs dispersion compensated pulses shown in Fig. 5 display dramatically different results. Figure 5(a) shows the pulse spectrum before amplification, Fig. 5(b) shows the pulse spectrum after amplification, Fig. 5(c) shows
the autocorrelation of the 750 fs pulses before and after amplification and Fig. 5(d) shows the measured gain dynamics. An enhancement of the long wavelength side and the short wavelength side of the amplified pulse spectrum are observed in Fig 5(b). The enhancement of the long wavelength side is a result of the low frequency instantaneous frequency associated with the fast gain depletion observed in Fig. 5(d) and the enhancement of the short wavelength side of the spectrum is a result of the high frequency instantaneous frequency associated with the partial gain recovery also observed in Fig 5(d). This partial gain recovery is a result of the cooling of hot carriers back to equilibrium as explained above. Figure 5(c) reveals a significant pulse broadening of the amplified pulses. These results clearly show that external cavity semiconductor mode-locked lasers can not support short pulses. The amplification of short pulses results in fast gain changes in the SOA imparting a nonlinear pulse chirp and broadening the pulses. In external cavity semiconductor mode-locked lasers, the combination of the dispersion of the cavity elements and the gain dynamics of the SOA and the SA, results in the production of long pulses with a predominant linear chirp, avoiding fast gain dynamics and nonlinearities in the SOA, allowing for a stable mode-locking operation [19].

3. SOA gain dynamics measurements for the amplification of multiwavelength pulses

The fast gain dynamics induced by the amplification of multiwavelength pulses in a semiconductor optical amplifier were measured. The experimental setup is shown in Fig. 6, where time-resolved pump-probe techniques were used for the measurements. The device under test is a 350 µm long AlGaAs based SOA with a double heterostructure design and is angle striped and antireflection coated [12]. The SOA is biased at a constant current of 200 mA. An external cavity semiconductor mode-locked laser is used as the pulse source for the pump-probe measurements, generating optical pulses of approximately 6 picoseconds in duration at a repetition rate of 271 MHz and 4 mW of average output power, with a spectral bandwidth of 4 nm, centered at 835 nm. The pulses are primarily linearly chirped, and can be externally compressed using a dispersion compensator.

The pulses from the mode-locked laser are divided unequally between the pump and the probe such that only a small part is used for the probe. The probe pulse duration is reduced to approximately 750 fs by linear dispersion compensation using a dual grating dispersion compensator [15]. The probe polarization is rotated 90 degrees, a variable neutral density filter is used to attenuate the probe power and a variable delay stage is used to delay the probe with respect to the pump.
The pump is obtained by passing the laser pulses through another dual grating dispersion compensator where the linear chirp is compensated and the pulse spectrum is spectrally sliced obtaining three wavelength channels of approximately 0.5nm FWHM each, with a 1.4 nm channel to channel separation. Since the pump is comprised of three phase correlated wavelength channels, the temporal profile is a burst of short pulses under a broad envelope. The temporal duration of a single pulse within the pulse burst is inversely proportional to the full spectral width encompassing all the wavelength channels, while the temporal duration of the pulse burst is inversely proportional to the spectral bandwidth of a single wavelength channel and the separation between pulses within the pulse burst is inversely proportional to the separation between wavelength channels.

The pump and probe pulses are coupled into the SOA under test, and the amplified probe power and spectrum are measured as a function of the delay between pump and probe. The strong pump pulses induce changes in the SOA gain, and the short probe pulses measure the gain change as a function of the delay between the pump and probe pulses. Cross polarized pump and probe and lock-in detection techniques are used to distinguish between the pump and probe after passing thru the SOA. Figures 7(a) and 7(b) show the pump spectrum before and after amplification. The salient feature of Fig. 7(b) is the additional wavelength channels generated by the multiwavelength pump via four wave mixing in the SOA, suggesting the interchange of energy between wavelength channels, leading to a small spectral and temporal reshaping of the multiwavelength pulses. Figure 7(c) shows the pump and probe autocorrelations and Fig. 7(d) plots the probe signal as a function of the delay between the pump and probe pulses, representing the SOA gain dynamics as the multwavelength pump is amplified. An overall reduction of the gain due to stimulated emission, which recovers on a nanosecond time scale, is observed in Fig. 7(d). In addition, a rapid oscillation of the gain caused by the periodic temporal nature of the phase coherent 3 wavelength channels is also observed. These transients are a result of carrier heating and carrier cooling effects due to the short pulses in the multiwavelength composite pulse profile.

![Fig. 7. Gain dynamics for the amplification of dispersion compensated multiwavelength pulses in a SOA. Pump spectrum (a), pump spectrum after amplification (b), pump, probe, and pump after amplification autocorrelations (c), and time resolved gain dynamics (d).](image)

As described in section two, owing to the large coupling among gain, carrier concentration, and refractive index, the rapid gain changes induce rapid index of refraction
changes resulting in a phase modulation that couples to the probe pulse via degenerate cross phase modulation. To observe this effect, a plot of the probe spectrum measured as a function of the delay between the pump and probe is shown in Fig. 8(a). In this plot, the probe spectra are normalized with respect to the gain of the SOA to observe only the spectral changes, not the gain changes. Also, the probe spectra are normalized with respect to the unperturbed probe spectrum, to yield a flat top spectrum as a reference. Changes in the spectrum of the probe due to cross-phase modulation induced by the pump are observed, where a peak wavelength (or frequency) periodically alternates between long and short wavelengths as depicted by the white line in Fig. 8(a). This line is plotted in Fig. 8(b) along with the measured SOA gain dynamics shown in Fig. 7(d). If this figure is analyzed with care it can be observed that the long wavelength peaks correspond to times when the gain is decreasing (instantaneous frequency shifted to low frequencies) and the short wavelength peaks correspond to times when the gain is recovering (instantaneous frequency shifted to high frequencies). Figure 8(a) clearly shows the temporal evolution of the phase modulation induced on a weak probe pulse by a strong multiwavelength pump pulse.

The measurement of the SOA gain under multiwavelength pulse amplification was repeated for chirped multiwavelength pulses. Experimentally, this was achieved by not compensating for the linear chirp impressed on the pump pulses obtained from the semiconductor mode-locked laser. In this case, the spectral filtering employed to create the pump pulse produces 3 mode-locked wavelength channels with a temporal skew, or delay, among wavelength channels and the composite pump pulse profile is broader with less temporal beating. Figure 9 shows the input and output spectra, the intensity autocorrelations and the time resolved gain, and Fig. 10 shows the time-resolved probe spectrum. In this case, the fast gain dynamics observed for the amplification of dispersion compensated multiwavelength pulses are not present, the wavelength channels associated with four wave mixing are greatly suppressed and the pump autocorrelation is broader with less temporal modulation owing to the temporal skew and the pulse broadening due to the pulse chirp. This leads to a slow gain depletion and results in the reduction of carrier heating and carrier cooling effects and a better power extraction from the SOA. In addition, the induced cross phase modulation effects are no longer evident when the probe spectrum is plotted as a function of the delay between the pump and the probe as observed in Fig. 10.

Fig. 8. Probe spectrum measured as a function of the delay between the pump and the probe for the amplification of dispersion compensated multiwavelength pulses in a SOA (a) and instantaneous frequency (peak wavelength) and measured SOA gain dynamics (d).

The measurement of the SOA gain under multiwavelength pulse amplification was repeated for chirped multiwavelength pulses. Experimentally, this was achieved by not compensating for the linear chirp impressed on the pump pulses obtained from the semiconductor mode-locked laser. In this case, the spectral filtering employed to create the pump pulse produces 3 mode-locked wavelength channels with a temporal skew, or delay, among wavelength channels and the composite pump pulse profile is broader with less temporal beating. Figure 9 shows the input and output spectra, the intensity autocorrelations and the time resolved gain, and Fig. 10 shows the time-resolved probe spectrum. In this case, the fast gain dynamics observed for the amplification of dispersion compensated multiwavelength pulses are not present, the wavelength channels associated with four wave mixing are greatly suppressed and the pump autocorrelation is broader with less temporal modulation owing to the temporal skew and the pulse broadening due to the pulse chirp. This leads to a slow gain depletion and results in the reduction of carrier heating and carrier cooling effects and a better power extraction from the SOA. In addition, the induced cross phase modulation effects are no longer evident when the probe spectrum is plotted as a function of the delay between the pump and the probe as observed in Fig. 10.
In general, all the nonlinear effects were decreased when amplifying chirped multiwavelength pulses. This is owing to the fact that the composite pulse profile is broadened and the temporal beating induced by the coherent nature of the multiwavelength pulses is reduced as a result of the pulse chirp.
4. External cavity multiwavelength semiconductor mode-locked laser intracavity gain dynamics

After studying the main nonlinearities present in the amplification of pulses from external cavity semiconductor mode-locked lasers in SOAs, the intracavity gain dynamics of an external cavity multiwavelength semiconductor mode-locked laser was measured revealing how multiwavelength lasers avoid these nonlinearities thereby making multiwavelength operation feasible.

The laser investigated is an external cavity semiconductor hybridly mode-locked laser in a multiwavelength configuration and is sketched in Fig. 11. The gain media is an AlGaAs semiconductor optical amplifier, similar to the ones used in the previous experiments. A multiple quantum well saturable absorber is used as passive mode-locking element, an etalon in combination with a spectral filter is used to establish multiwavelength operation and the laser output is obtained by a 50 % output coupler. The etalon is a 0.5 mm thick solid glass etalon with 70 % reflecting surfaces resulting in transmission peaks separated 0.48 nm at 835 nm, with a finesse of 8. The spectral filter consists of an 1800 lines/mm grating, a 15 cm focal length lens, a mirror, and a slit. The grating, lens and mirror are located 15 cm from each other (lens’ focal length) and the slit is used to select the desired spectral bandwidth. In this configuration, the spectral filter allows the amplification of 3 etalon transmission peaks around 835 nm (three mode-locked wavelength channels).

![Fig. 11. External cavity multiwavelength semiconductor hybrid mode-locked laser intracavity gain dynamics measurement setup.](image)

The probe pulses used to measure the intracavity gain dynamics of the multiwavelength laser were obtained from an external cavity hybrid mode-locked semiconductor laser in a linear configuration, combined with a dual grating dispersion compensator, resulting in pulses of approximately 1 ps in duration with a center wavelength of 839.5 nm and 3 nm of spectral bandwidth. It should be noted that the gain changes resulting from carrier heating and carrier cooling effects in the SOA modify the entire gain spectrum. Since the center wavelength of the probe and the multiwavelength pulses are sufficiently close to each other and to the SOA gain peak, the probe pulse senses the carrier heating and carrier cooling gain changes induced by the multiwavelength pulses. The multiwavelength laser and the probe laser are synchronized by having the same cavity length and sharing the same radio frequency source. Hybrid mode-locking of the multiwavelength laser was achieved for an SOA DC bias of 150 mA with 250 mW of radio frequency (RF) signal power at 450 MHz, yielding 4 mW of...
average output power. An identical SOA was used to amplify the multiwavelength pulses to approximately 20 mW. The multiwavelength pulse spectrum is shown in Fig. 12(a) and its autocorrelation is shown in Fig. 12(b), where the modulation observed is an indication of the phase correlation between wavelength channels. Due to the long pulse duration of the composite pulse and to the limited time window of the autocorrelator used, a good estimate of the pulse duration of the multiwavelength pulses can not be obtained from the autocorrelation. The measured timing jitter between lasers was less than 2 ps and it should be noted that the jitter is less than the temporal beat period defined by the separation between wavelength channels and will allow the resolution of fast gain dynamics if present. In this case, as observed in Fig. 12(b), the beat period of the multiwavelength pulses is approximately 5 ps.

The individual wavelength channels were separated using a spectral filter similar to the filter in the multiwavelength laser cavity and measured using a 15 GHz fast photo-detector and a sampling scope. The measured pulses corresponding to each individual wavelength channel are shown in Fig. 12(c) where it can be observed that the pulses do not temporarily coincide. These pulses are chirped and have a time duration several times the Fourier transform limit. The SOA gain and the dispersion introduced by the different cavity elements determine the intensity and the relative temporal pulse position of each channel. In this case channel 2 and channel 3 are temporally close to each other and channel 1 is delayed by several tens of picoseconds. The relative temporal pulse position of the individual channels can change with the alignment of the laser cavity, however there is always a temporal skew among wavelength channels. Note that the negative signal values in Fig. 12(c) are an artifact from the impulse response of the photo-detector.

To measure the temporal evolution of the SOA gain in the multiwavelength laser, the probe pulses were introduced into the laser cavity by using a pellicle beam splitter as shown in Fig. 11. The probe power coupled into the multiwavelength laser (a few micro watts of average power), is sufficiently low to avoid disturbing the multiwavelength operation of the laser. A variable delay is used to change the relative delay between the probe and the multiwavelength pulses in the multiwavelength laser cavity. The probe pulses measure the SOA gain as a function of the delay between the probe and the multiwavelength pulses, representing the temporal evolution of the SOA gain.

The laser output contains the probe pulses after measuring the SOA gain and the multiwavelength pulses; however, the spectra of the probe and the multiwavelength pulses do not overlap and are separated via spectral filtering. A chopper and a lock-in amplifier were used on the probe to obtain clean measurements. Figure 13(a) shows the measured temporal evolution of the SOA gain. The gain depletion and gain recovery signal associated with the amplification of the multiwavelength pulses is superimposed on a gain that is modulated by the bias current. The modulated gain is measured by measuring the temporal evolution of the gain while blocking the laser feedback and is used as a reference to normalize the measured gain under multiwavelength operation. The modulated gain is shown in Fig. 13(b) and the
normalized gain is shown in Fig. 13(c). The chosen time window in Figs. 13(a), 13(b) and 13(c) is sufficient to observe the important gain features during one cavity round trip. Times beyond this window correspond to a slow gain recovery between the amplification of consecutive pulses.

Due to the multiwavelength laser cavity configuration, the multiwavelength pulses pass through the SOA twice per cavity round trip, traveling in opposite directions each time, while the probe pulses pass through the SOA in only one direction measuring the SOA gain. Two gain depletion regions can be observed in Fig. 13(c). The first corresponds to the multiwavelength and probe pulses passing through the SOA in opposite directions and the second corresponds to multiwavelength and probe pulses passing through the SOA in the same direction. A close-up of the second gain depletion is shown in Fig. 13(d), where the important feature is that the SOA gain is depleted slowly thus avoiding nonlinearities in the SOA during the amplification process.

\[ h(t) = u(t)[a_1e^{-t/T_0} + a_2(1 - e^{-(t/T_{ia})})e^{-(t/T_{ia})} + a_3e^{-(t/T_{ia})}] + a_4\delta(t) \]  

where \( u(t) \) is the unit step function ensuring casualty, the first term of the sum inside the square brackets represents the long lived stimulated carrier density change \((T_0 \approx 1\text{ns})\), the second term is the carrier heating response, with \( T_{ia} \) being the carrier heating delay \((T_{ia} \approx 120\text{ns})\) and \( a_1, a_2, a_3, a_4 \) the corresponding gain coefficients.

In summary, the intracavity gain dynamics of an external cavity hybrid semiconductor mode-locked laser was measured under multiwavelength operation, showing how the pulses corresponding to different wavelength channels are chirped and temporally skewed resulting in a broad composite pulse profile and a slow depletion of the gain, avoiding nonlinearities in the SOA, thus making multiwavelength operation attainable.

5. Numerical simulations

Numerical simulations were made to support the experimental results. An approximation of the SOA impulse response was used to simulate the gain dynamics for each experimental case presented in this paper. The impulse response function employed is [16]:

In summary, the intracavity gain dynamics of an external cavity hybrid semiconductor mode-locked laser was measured under multiwavelength operation, showing how the pulses corresponding to different wavelength channels are chirped and temporally skewed resulting in a broad composite pulse profile and a slow depletion of the gain, avoiding nonlinearities in the SOA, thus making multiwavelength operation attainable.
fs) and $T_{1b}$ the carrier cooling time ($T_{1b}$~1ps), the third term represents spectral hole burning ($T_2$~120 fs), and the delta function represents instantaneous processes.

The SOA gain change resulting from the amplification of a pulse is equal to the convolution of the intensity pulse profile and the impulse response:

$$\Delta g(t) = \int_{-\infty}^{\infty} h(t-t_1) I_{\text{pump}}(t_1) dt_1 \quad (2)$$

In the pump-probe measurements of the SOA gain dynamics presented in this paper, the probe power was measured as a function of the delay between the pump and probe using a slow photo detector which averages the probe power over time, thus the measured probe signal is equivalent to the cross-correlation of the probe pulse intensity profile and the gain changes induced by the pump pulses:

$$S(\tau) = \int_{-\infty}^{\infty} I_{\text{probe}}(t-\tau) \Delta g(t) dt \quad (3)$$

The pulse chirp from external cavity semiconductor mode locked lasers is predominantly linear (quadratic phase) with a smaller cubic phase component. By compensating the quadratic and cubic phase, pulses close to the Fourier transform limit can be obtained from these lasers [14]. To simulate the intensity pulse profile, the square root of the pulse spectrum is calculated, representing the spectral field for Fourier transform limited pulses, then quadratic and cubic phase are added to the spectral field to broaden the pulses in time. The spectral field is inverse Fourier transformed and multiplied by its complex conjugate obtaining the simulated temporal pulse profile. The autocorrelation of the simulated pulse is calculated and compared with the measured autocorrelation, and the spectral phase is modified until a satisfactory fit is obtained. This is done for each one of the SOA gain measurements presented in this paper. It is important to emphasize that this simulations represent an approximation and not an exact fit of the experimental results.

The parameters used to generate the impulse response function were obtained from previous simulations [18], and adjusted until the simulated gain dynamics match the experimental results obtained for the amplification of the 750 fs pulses presented in section 2. In this case the pump and probe pulses were identical and were obtained by compensating the linear chirp (quadratic phase) of the pulses from the laser source, hence the pulse profile was simulated by adding only cubic spectral phase to the pulse spectrum. The resulting impulse function obtained is shown in Fig. 14 and is used for the simulation of the SOA gain dynamics of the other cases.

![Fig. 14. SOA impulse function.](image-url)
The simulated dispersion compensated multiwavelength pulses were obtained by spectrally filtering the simulated 750 fs pulses, the simulated long 6.5 ps pulses were obtained by adding quadratic spectral phase to the simulated 750 fs pulses and the simulated non-dispersion compensated multiwavelength pulses were obtained by spectrally filtering the 6.5 ps pulses. This is equivalent to the experimental approach used to obtain these pulses. The results from the numerical simulations are summarized in Fig. 15, where it can be observed that the numerical results are in a good agreement with the experimental ones.

![Fig. 15. Numerical simulations for the amplification of 750 fs pulses, 6.5 ps pulses, dispersion compensated pulses and multiwavelength pulses with dispersion in a SOA.](image)

To simulate the intracavity gain dynamics of the multiwavelength laser presented in section 4, the intracavity pulses were simulated by taking the square root of the measured spectrum, then by manipulating the spectral phase of each wavelength channel the corresponding pulses were broadened and temporally skewed to match the measured ones. Figure 16 shows the measured spectrum, the measured pulses corresponding to each wavelength channel, the simulated pulses, the composite pulse profile resulting from the combination of the three phase correlated wavelength channels, the simulated autocorrelation and the simulated gain dynamics. It can be observed in Fig. 16(f) that the simulated gain dynamics is characterized by a slow gain depletion with no significant fast gain changes. The numerical simulations results agree well with the experimental ones, constituting theoretical support for the experimental conclusions derived from this work.
6. Conclusion

The gain dynamics of a semiconductor optical amplifier were measured for the amplification of 6.5 ps and 750 fs pulses. The 6.5 ps pulses were obtained from an external cavity semiconductor mode-locked laser and the 750 fs pulses were obtained by compensating the linear dispersion of the 6.5 ps pulses. It was shown how the 750 fs pulses trigger carrier heating and carrier cooling effects not observed for the amplification of the 6.5 ps pulses.

The gain dynamics of the SOA were also measured for the amplification of multiwavelength pulses. The multiwavelength pulses were obtained by spectrally slicing the 750 fs dispersion compensated pulses and the 6.5 ps pulses in three wavelength channels. The coherent nature of the wavelength channels results in a temporal beating of the composite pulse profile. For the amplification of the spectrally sliced 750 fs dispersion compensated pulses, the temporal beating caused by the phase correlation of the three wavelength channels results in a fast oscillating gain inducing carrier heating, carrier cooling, four wave mixing and an oscillating instantaneous frequency imparted on the composite pulse. It was shown that these nonlinearities decrease when the multiwavelength pulses contain the chirp from the external cavity semiconductor mode-locked laser pulse source.

The intracavity gain dynamics of an external cavity multiwavelength semiconductor mode-locked laser was measured, revealing a temporal skew among pulses corresponding to different wavelength channels. The temporal skew and pulse chirp broaden the composite pulse profile and decrease the temporal beating due to the phase correlation between wavelength channels, avoiding non-linearities and decreasing the gain competition between wavelength channels, enabling multiwavelength operation.

Numerical simulations were made for each of the experimental cases presented in this paper supporting the experimental results.

In general, in external cavity semiconductor mode-locked lasers, the inherent chirp of the pulses broadens the pulse profile resulting in a slow gain depletion. This slow gain depletion decreases phase modulation and carrier heating and carrier cooling effects in the gain media (SOA) and supports mode-locked operation.