# Self-validating technique for the measurement of the linewidth enhancement factor in semiconductor lasers

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**Abstract:** A new method for measuring the linewidth enhancement factor (α-parameter) of semiconductor lasers is proposed and discussed. The method itself provides an estimation of the measurement error, thus self-validating the entire procedure. The α-parameter is obtained from the temporal profile and the instantaneous frequency (chirp) of the pulses generated by gain switching. The time resolved chirp is measured with a polarization based optical differentiator. The accuracy of the obtained values of the α-parameter is estimated from the comparison between the directly measured pulse spectrum and the spectrum reconstructed from the chirp and the temporal profile of the pulse. The method is applied to a VCSEL and to a DFB laser emitting around 1550 nm at different temperatures, obtaining a measurement error lower than ± 8%.



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## 1. Introduction

The Linewidth Enhancement Factor, also known as the α-parameter or Henry factor [1], of semiconductor lasers is a relevant quantity which affects several aspects of the device behavior, e. g. the frequency chirp in directly modulated sources and the dynamic response of the laser when subjected to optical injection or feedback. The α-parameter is defined as [1]: $\alpha = (4\pi/\lambda)dn/dN\cdot(dG/dN)^{-1}$, where $\lambda$ is the emission wavelength and $dn/dN$ and $dG/dN$ are the derivatives of the refractive index, $n$, and of the gain, $G$, with respect to the carrier density, $N$, respectively.

Precise measurement of the linewidth enhancement factor is relevant for device modeling and characterization and its knowledge is often required in directly modulated fiber optics links where the maximum transmission length is limited by the transmitter chirp. Several techniques have been developed for the measurement of the α-parameter in semiconductor lasers. They can be grouped in three classes of measurements: i) based on continuous wave (CW) spectral measurements [2, 3], ii) based on direct intensity modulation in the small [4, 5] and large [6–8] signal regimes, and iii) based on optical injection [9] or feedback [10]. An exhaustive description and comparison of the aforementioned techniques is given in [11–13].

A common point to previously reported techniques is that no information on the measurement error is provided. The error estimation of the α-parameter measurement is obtained, when it is the case, from several measurements and from a statistical analysis of the results. As pointed out in [12, 13], different α-parameter values can be obtained for the same device depending on the selected measurement technique. Thus, the estimation of the experimental error would be a great advantage with respect to presently available techniques in order to validate the measurements, and a self-validating technique could be used as a reliable reference for comparison purposes.

In this manuscript, we propose the determination of the α-parameter from the intensity and Time Resolved Chirp (TRC) measurements of the pulses obtained with a Gain Switched (GS) [14] semiconductor laser. A great advantage of our approach is that the accuracy of the measurement can be estimated from the comparison between the reconstructed pulse spectrum and the independently measured spectra.

The TRC measurements are performed applying the Phase Reconstruction using Optical Ultrafast Differentiation (PROUD) technique [15], using a fiber based birefringent interferometer as an optical differentiator [16]. The proposed method is applied to a Vertical Cavity Surface Emitting Laser (VCSEL) and to a Distributed Feedback (DFB) lasers both emitting around 1550 nm.

This paper is organized as follows: in Section 2, we present the description of the method, in Section 3 the experimental technique and the results are described, in Section 4 the error estimation is discussed and finally in Section 5, the main conclusions are summarized.

## 2. Method description

The basic idea underlying the proposed technique is that from the intensity and chirp measurements of the pulses generated from a GS laser the α-parameter can be determined and the pulse spectrum can be reconstructed. Thus, if a second, direct and independent spectral measurement is available, the accuracy of the TRC and α-parameter measurements can be estimated from the comparison between the reconstructed and measured spectra.

The laser instantaneous frequency, *ν(t)*, (i.e. the chirp), can be expressed as a function of the output intensity, *P(t)* by [17]:

$$\nu(t) = \frac{\alpha}{4\pi}\left(\frac{1}{P(t)}\frac{dP(t)}{dt} + \kappa P(t)\right) \tag{1}$$

where κ is the adiabatic chirp coefficient, which depends on the laser internal parameters.

The first term on the right-hand side of Eq. (1) is usually referred to as the *transient* chirp term, as it is dominant during the rising and falling edge of the optical pulse. The second term, proportional to *P(t)*, is the *adiabatic* chirp term and it takes into account the dependence of the laser frequency on the output power, due to the effect of the non linear gain compression on the threshold carrier density. Thus, if *P(t)* and *ν(t)* are known, fitting to Eq. (1) allows the extraction of α and κ. Under gain-switching operation, only the first spike of the relaxation oscillations is excited and therefore the adiabatic term in Eq. (1) can be neglected, since the steady state of the output is not reached [17]. Then, the chirp *ν(t)* is proportional to $(P(t))^{-1}dP(t)/dt$ and the *α*-parameter can be obtained from a simple linear fit.

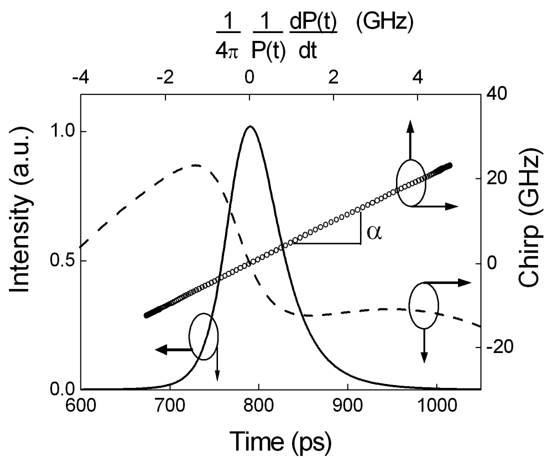


Fig. 1. Simulation results. Solid line: pulse intensity (left and bottom axes). Dashed line: time resolved chirp (right and bottom axes). The open circles represent the chirp plotted as a function of $(4\pi P(t))^{-1}dP(t)/dt$ (right and upper axes).

Figure 1 shows the intensity and chirp temporal profiles of a GS semiconductor laser, obtained by numerical simulation. Typical semiconductor laser parameters [18] have been used in solving the well known rate equations for carriers, amplitude and phase of the optical field. The linear dependence of the chirp *ν(t)* as a function of $(P(t))^{-1}dP(t)/dt$ is clearly shown in Fig. 1 and the value of the α-parameter used in simulations is recovered from the slope of the curve after linear fitting.

In the experimental procedure, the pulse spectral intensity can be reconstructed from *P(t)* and *ν(t)* for the comparison with the independently measured spectrum, by the following simple procedure. First, the pulse optical phase, *φ(t)*, is obtained by numerical integration of the measured instantaneous frequency *ν(t)*, as: $\varphi(t) = \int 2\pi\nu(t)dt + \varphi_0$, where $\varphi_0$ is a non relevant initial phase. The signal complex field *E(t)* is then easily calculated as $E(t) = \sqrt{P(t)}\exp(j\phi(t))$, where *j* denotes the imaginary unit. Finally, the pulse spectral intensity is reconstructed as the squared magnitude of the Fourier transform of the signal complex field.

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The retrieved spectrum obtained by this procedure from an ideal TRC measurement, free from experimental errors, should perfectly match the directly measured pulse spectrum. Thus, the comparison between the two spectra allows to define a measurement spectral error in percent units $\varepsilon_S$ as:

$$\varepsilon_S = 100 \cdot \frac{\int \left| I_m(f) - I_r(f) \right| df}{\int I_m(f)\, df} \qquad (2)$$

where $I_m(f)$ and $I_r(f)$ are the measured and reconstructed pulse intensity spectra, respectively, and the integrals extent over the entire frequency range. As it will be described in detail in section 4, the experimental value of $\varepsilon_S$ is a clear indication of the quality of the TRC measurements and therefore of the accuracy of the extracted α-parameter.

### 3. Experimental results

The proposed method has been applied to two commercial devices emitting in the 1550 nm region: a Distributed Feedback laser (DFB, JDS Uniphase) and a Vertical Cavity Surface Emitting Laser (VCSEL, Raycan).

Pulses were generated by gain switching the lasers with a DC current source providing a current $I_{BIAS}$ and a Pulse Pattern Generator (Anritsu MP1808) providing a current pulse train. The lasers were temperature controlled with a Thermo Electric Cooler and the measurements were performed at different temperatures between 20° C and 40° C. The driving conditions were chosen in order to excite only the first spike of the relaxation oscillations. $I_{BIAS}$ was set close to the threshold current $I_{TH}$ ($I_{BIAS}$ = 1.1 $I_{TH}$) and the electrical excitation pulse widths were 250 ps and 125 ps for the VCSEL and the DFB laser, respectively. More details on the experimental set-up and on the pulse properties of a similar GS VCSEL can be found in [19]. The duty cycle of the electrical pulse train was kept low (5%) to avoid the heating of the active region caused by current injection.

The TRC measurement technique used in this work is based on the PROUD method [15]. In PROUD, the instantaneous frequency is obtained from the original, *P(t)*, and the differentiated, *Q(t)*, pulse intensity temporal profiles by applying the following expression:

$$\nu(t) = \sqrt{\left[ \left( \frac{\sqrt{Q(t)}}{A} \right)^2 - \left( \frac{d(\sqrt{P(t)})}{dt} \right)^2 \right] \Big/ P(t)} - \Delta f \qquad (3)$$

where *A* is the differentiator slope in the frequency domain at the input signal frequency and *Δf* is the frequency difference between the differentiator resonance frequency and the input signal frequency (see [15] for details).

The fiber based birefringent interferometer described in [16] was used as the optical differentiator and *P(t)* and *Q(t)* were measured with a fast photodiode and an oscilloscope (20 GHz bandwidth). The signal is amplified with an Erbium Doped Fiber Amplifier (EDFA) before entering the interferometer. The spectra of the original and differentiated pulses are measured with an Optical Spectrum Analyzer (OSA), Ando AQ-6315A, and the ratio between the two spectra is used to determine the differentiator slope *A*.

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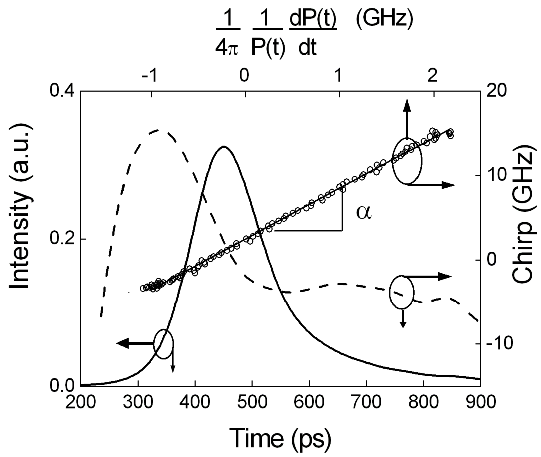


Fig. 2. Experimental results obtained with the 1550 nm VCSEL. Solid line: pulse intensity (left and bottom axes). Dashed line: time resolved chirp (right and bottom axes). The open circles represent the chirp plotted as a function of $(4\pi P(t))^{-1}dP(t)/dt$ (right and upper axes).

Figure 2 shows, as an example, the measured intensity $P(t)$ and the chirp $\nu(t)$ as obtained with the VCSEL at 25 °C. The expected negative frequency variation during the pulse, very similar to the theoretical results in Fig. 1, is clearly observed. The predicted linear dependence of the chirp $\nu(t)$ versus $(P(t))^{-1}dP(t)/dt$ is also apparent in this figure and confirms the assumption that the adiabatic chirp term of Eq. (1) can be neglected. The linear fitting yields a value of 5.7 for the α-parameter in this case.

For a proper comparison of the reconstructed spectrum with the directly measured pulse spectrum, the former was convolved with the measured spectral response of the OSA filter, with a Full Width Half Maximum (FWHM) bandwidth of 0.05 nm (6.25 GHz). The measured, reconstructed and convolved spectra of the pulse in Fig. 2 are shown in Fig. 3. The value obtained for the spectral error $\varepsilon_S$ in this case is 5.3%.

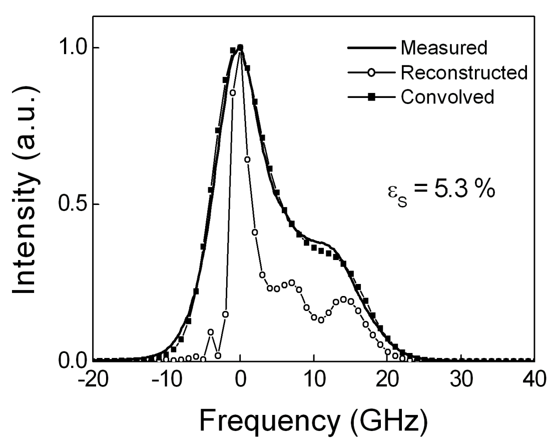


Fig. 3. Comparison between the measured (black solid line), reconstructed (open circles) and convolved (solid squares) spectra of the pulse shown in Fig. 2.

The reconstructed spectrum shows intensity maxima at frequency separations (5 - 10 GHz) similar to the expected values of the relaxation oscillation frequencies for this range of bias and excitation current. This feature is lost in the convolved spectrum, due to the finite resolution of the OSA. Thus, the limited OSA resolution actually reduces the measured spectral error, as it smoothes both the reconstructed and the measured spectral profiles. This must be taken into account for the proper estimation of the error in the α-parameter from $\varepsilon_S$ as it is discussed in section 4.

In order to further check the consistency of the method and the reproducibility of the measurements under different experimental conditions, experiments were performed at different laser case temperature between 20°C and 40°C. In this short temperature range no significant differences in the value of α are expected [11]. The laser threshold current was measured at each temperature and $I_{BIAS}$ was varied accordingly ($I_{BIAS} = 1.1 \cdot I_{TH}$), while the electrical pulse amplitude, duration and duty cycle were not changed. Ten measurements were performed at each temperature for each device. Figure 4 shows the average values of the α-parameter obtained at each temperature for the DFB and for the VCSEL. The obtained values range between 3.5 and 3.7, and between 5.7 and 6, for the DFB and the VCSEL, respectively. Therefore, within the experimental error the values of the α-parameter are constant as expected. The reproducibility of the results was good, as the standard deviation of the measurements was better than 4% in all the cases. The error bars shown in Fig. 4 were obtained from the spectral error $\varepsilon_S$ of each measurement, as explained in section 4, combined with the standard deviation of the ten measurements performed at each temperature.

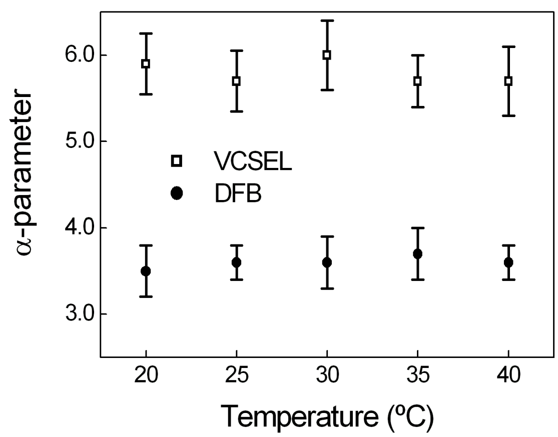


Fig. 4. Linewidth enhancement factor obtained at different temperatures for the DFB laser (solid circles) and for the VCSEL (open squares).

## 4. Error estimation

There have been many experimental reports dealing with measurement techniques and results on the α-parameter for different materials and structures of semiconductor lasers (see [11–13], and references herein). However, there is a strong uncertainty between experimental results for the α-parameter of the same laser when using different characterization techniques. For instance Fordell et al. [12] report values ranging between 3.5±0.4 and 6.2±0.3 for an air-post 760 nm single-mode VCSEL. In general, a reliable determination of the α-parameter is a difficult task. The problem is partly due to the ambiguity of the definition of the α-parameter, considered simultaneously a material and a device parameter [11], and also caused by the random and/or systematic errors of the experimental techniques. Most of the techniques are based on simplified laser models which assume carrier and photon uniformity within the cavity, and therefore provide an average or device value, which can be different depending on the particular technique. In consequence, it is very important to find out measurement techniques which incorporate validation mechanisms.

In this section, we estimate the error limit in the α-parameter from the spectral error and from numerical simulations of the complete measurement technique. In our case, the proposed technique, based on Eq. (1), implies that we calculate the effective α-parameter, i. e. the α-parameter related to the semiconductor material and to the laser structure, at the threshold carrier concentration and at the lasing wavelength.

The basic idea to estimate the error in the α-parameter is to use the independently measured spectrum to calculate the spectral error $\varepsilon_S$, and to relate $\varepsilon_S$ with the α-parameter error by means of numerical simulations. We identify three main error sources in our implementation: (i) the jitter and noise in the temporal profiles of the original and differentiated pulses, (ii) the uncertainty in the determination of the differentiator slope *A* and (iii) the non idealities of the optical differentiator. For the pulse durations considered in the experiments, the finite bandwidth of the photodiode and oscilloscope (20 GHz) does not affect the error calculation, as confirmed by simulations.

The noise and jitter contributions affect the determination of the α-parameter, mainly due to the time derivative of *P(t)* in Eq. (1). In consequence, around 400 temporal traces have been acquired and averaged at each measurement, in order to minimize the contribution of stochastic fluctuations at the turn-on of the GS laser and of the detector noise.

The differentiator parameters *A* and *Δf* are experimentally obtained from the original and differentiated pulse intensity spectra at each measurement. Small fluctuations of the laser spectrum or of the differentiator transfer function introduce errors in the estimation of *A* and *Δf*. On the other hand, the value of *Δf* does not actually affect the α-parameter measurement, as *Δf* contributes with a constant shift to the chirp *ν(t)* and it does not modifies the slope of the plot of *ν(t)* versus $(P(t))^{-1}dP(t)/dt$. Thus, the uncertainty of the differentiator slope *A* is considered as the main source of error in our experiments, and we consider that the fluctuations in the differentiator response give rise to the standard deviation of 4% in a set of measurements in nominally identical conditions previously commented.

The non idealities of the PROUD technique have been presented and discussed in detail in [20]. The physical implementation of an ideal optical differentiator with a real interferometer implies that an error greater than zero is expected in the determination of *ν(t)* and consequently in $\varepsilon_S$ and in the α-parameter. The importance of this error is discussed further in the text.

In order to relate the spectral error $\varepsilon_S$ with the α-parameter error the entire experimental technique was simulated. The initial optical pulse was obtained from the standard rate equations considering estimated laser parameters which provided pulses similar in shape and duration to those experimentally measured. The simulated pulses were filtered by the calculated frequency response of the birefringent interferometer, and then the chirp and the α-parameter were calculated using Eqs. (1) and (3). The spectral error was calculated from the comparison between the initial pulse spectrum and the pulse spectrum reconstructed from chirp, taking into account the spectral response of the OSA filter. The error in the α-parameter $\varepsilon_\alpha$ in percent units is defined as:

$$\varepsilon_\alpha = 100 \cdot \frac{\left|\alpha_{RE} - \alpha_{rec}\right|}{\alpha_{RE}} \tag{4}$$

where $\alpha_{RE}$ is the value of the α-parameter introduced in the rate equations of the laser and $\alpha_{rec}$ is the recovered value after simulation of the entire measurement set-up.

The influence of the uncertainty in the value of the differentiator slope *A* in the simulation results is illustrated in Fig. 5, where $\varepsilon_\alpha$ and $\varepsilon_S$ are shown as a function of $A/A_{NOM}$, where *A* is the value used in Eq. (3) to recover the chirp of the simulated pulse and $A_{NOM}$ is the nominal value extracted from the linearization of the interferometer transfer function. The spectral error $\varepsilon_S$ is shown for different values of the OSA filter bandwidth, while $\varepsilon_\alpha$ is independent of the OSA bandwidth, as the α-parameter is obtained from the temporal intensity and chirp profiles. The minimum errors, obtained as expected for $A/A_{NOM} = 1$, are greater than zero due to the non ideality of the implemented optical differentiator. For our particular polarization interferometer and pulse characteristics the minimum error in the α-parameter is around 1%.

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The error in the α-parameter $\varepsilon_\alpha$ increases almost linearly by increasing or decreasing the value of $A$, as it can be easily understood from Eqs. (3) and (1). In our experimental conditions, the first term below the square root in the right hand side of exp. (3) is much greater than the second term, and therefore an increase of $A$ correspond to a decrease of the extracted chirp. Equation (1) shows that a decrease of the chirp corresponds to a decrease of the calculated (or measured) α-parameter. Similarly, a decrease of $A$ results in a value of the α-parameter higher than the original one.

When the OSA bandwidth increases, $\varepsilon_S$ becomes smaller, because the original and reconstructed spectra are increasingly smoothened. As it is shown in Fig. 5, the largest values of $\varepsilon_S$ are obtained in the case of a filter bandwidth of 0.1 pm, corresponding to the case in which the OSA resolution does not affect the calculation of $\varepsilon_S$. For a large bandwidth of 1 nm, $\varepsilon_S$ is very small (~0%) in the entire range of $A$, due to the high smoothing of the spectral features, resulting in an unacceptable error underestimation.

For the OSA bandwidth used in our experiments (0.05 nm), $\varepsilon_S$ is slightly larger or equal to $\varepsilon_\alpha$ in the considered range of $A/A_{NOM}$, resulting in an upper bound to the errors obtained in the α-parameter measurements.

According to the results shown in Fig. 5, the α-parameter error in our set-up is approximately the spectral error, and considering that $\varepsilon_\alpha$ expresses the over- or underestimation of the α-parameter (see Eq. (4), we calculate the α-parameter accuracy as ± $\varepsilon_S$. The maximum experimental spectral error was 7% in all the performed experiments, yielding a maximum error in the α-parameter of ± 7% for each measurement. Considering the additional random error of 4% and assuming uncorrelated error sources, we estimate ± 8% for the maximum error. The error bars in Fig. 4, where the averaged value of the α-parameter at each temperature is plotted, have been calculated by combining the averaged spectral error and the random error at each temperature.

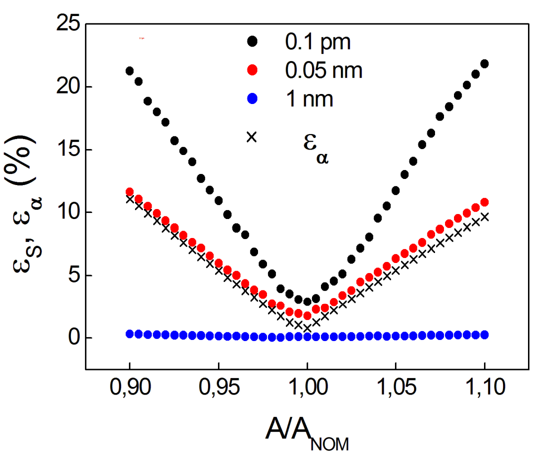


Fig. 5. α-parameter error as a function of the differentiator slope normalized to the nominal value, and spectral error for different OSA bandwidths.

## 5. Conclusions

In summary, we have demonstrated a novel experimental approach for the calculation of the α-parameter of semiconductor lasers, based on the time resolved chirp measurement of the pulses generated in gain switching conditions. The method relies on the possibility of deriving both the α-parameter and the pulse spectrum from the time resolved chirp and the temporal profile of the pulse intensity. The main advantage of our approach with respect to previously reported techniques is that the method itself allows the estimation of the experimental error in the α-parameter, through a comparison between the reconstructed and the directly measured

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pulse spectra, thus self-validating the entire procedure. The method is very simple to be applied when TRC measurements are available. In comparison with other techniques for the α-parameter determination, it does not provide the dependence of this parameter with the wavelength or carrier concentration. The method has been applied to a VCSEL and to a DFB laser emitting at around 1.5 μm, with estimated error in the α-parameter of around ± 8% at different room temperatures.

Although for demonstration purposes we have used the PROUD method based on a birefringent fiber interferometer as the TRC measurement technique, it is worth noting that the approach is independent of the TRC measurement technique, as long as the temporal profile and the TRC of the pulse, on one hand, and an independent measurement of the pulse spectrum on the other are available.

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