# Gain Compression and Above-Threshold Linewidth Enhancement Factor in 1.3-$\mu$m InAs–GaAs Quantum-Dot Lasers

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***Abstract*—Quantum-dot (QD) lasers exhibit many useful properties such as low threshold current, temperature and feedback insensitivity, chirpless behavior, and low linewidth enhancement factor ($\alpha_H$-factor). Although many breakthroughs have been demonstrated, the maximum modulation bandwidth remains limited in QD devices, and a strong damping of the modulation response is usually observed pointing out the role of gain compression. This paper investigates the influence of the gain compression in a 1.3-$\mu$m InAs–GaAs QD laser and its consequences on the above-threshold $\alpha_H$-factor. A model is used to explain the dependence of the $\alpha_H$-factor with the injected current and is compared with AM/FM experiments. Finally, it is shown that the higher the maximum gain, the lower the effects of gain compression and the lower the $\alpha_H$-factor. This analysis can be useful for designing chirpless QD lasers with improved modulation bandwidth as well as for isolator-free transmission under direct modulation.**

***Index Terms*—Gain compression, linewidth enhancement factor, quantum dot, semiconductor laser.**

## I. Introduction

QUANTUM-DOT (QD) lasers have attracted a great deal of interest in the last decade owing to their expected remarkable properties arising from charge carrier confinement in three spatial dimensions [1]. Low threshold current densities and high material gain [2], [3], temperature insensitivity [4], and near-zero linewidth-enhancement factor ($\alpha_H$-factor) at the lasing wavelength [5], [6] have been reported. This latter property combined with a high damping factor [7] is of utmost importance because it should increase the tolerance to optical feedback in these devices and may offer potential advantages for direct modulation without transmission dispersion penalty. Directly modulated QD lasers may hence play a major role in next-generation telecommunication links for cooler-less and isolator-free applications. Much effort has been devoted to the GaAs-based QD material system for emission in the 1.3-$\mu$m band, owing to a better material maturity [2]–[6] allowing the demonstration of temperature insensitive 10Gb/s transmission [8], [9]. Although many breakthroughs have already been demonstrated, the maximum modulation bandwidth remains limited to 10–12 GHz for lasers operating in the 1300–1550 nm bands, much below the best values reported for quantum-well (QW) lasers. At the same time, a strong damping of the modulation response is usually observed in QD devices, pointing to the role of the gain compression, which physically comes from the redistribution of carriers. Only devices exploiting tunnel injection [10], p-doping [4], [11], gain-lever effect [12], [13] or injection-locking [14] may improve the modulation bandwidth. Among the various properties of QD lasers, the $\alpha_H$-factor is one of the most important and is used to distinguish the behavior of semiconductor lasers with respect to other types of lasers [15]. The $\alpha_H$-factor influences several fundamental aspects of semiconductor lasers, such as the linewidth [16] or the laser behavior under optical feedback [17]. In the case of QD lasers, several models at the early stages have predicted a near-zero $\alpha_H$-factor due to the discrete density of states. Different groups have reported different values of the $\alpha_H$-factor associated with different techniques: for instance, a negative value to about 2 has been reported [18], [19]. On the other hand, an $\alpha_H$-factor as low as 0.1 has been measured in single-stack QD lasers [20] while a minimum of about 1.0 has been observed in a multistack sample [21]. It has been shown that the various techniques commonly used to measure the $\alpha_H$-factor can lead to different values when applied to QD lasers [22]. It is well known that the so-called linewidth enhancement factor can be written as

$$\alpha_H = -\frac{4\pi}{\lambda}\frac{dn/dN}{dg/dN} = -\frac{4\Gamma\pi}{\lambda}\frac{dn/dN}{dG_{\rm net}/dN} \quad (1)$$

where $g$ is the material gain. The $\alpha_H$-factor depends on the ratio of the evolution of the refractive index $(n)$ with the carrier density $(N)$ to that of the differential gain $(dg/dn)$. $\Gamma$ is the optical confinement and $G_{\rm net} = \Gamma g - \alpha_i$ is the net modal gain where $\alpha_i$ is the internal loss coefficient. In most cases, the $\alpha_H$-factor is detected by using the Hakki–Paoli method which, relies on direct measurement of the refractive index change and the differential gain as the carrier density is varied by slightly changing the current of a semiconductor laser in subthreshold operation. This method is applicable only below threshold and does not correspond to an actual lasing condition. A more reliable technique to measure the $\alpha_H$-factor is the AM/FM method, which relies

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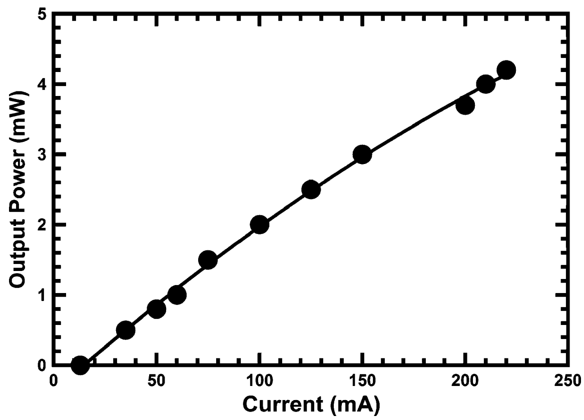


Fig. 1. $L(I)$ characteristic of the InAs–GaAs QD laser under study. At room temperature, the threshold current for the GS is 13 mA and the external differential efficiency is about 0.02 W/A.

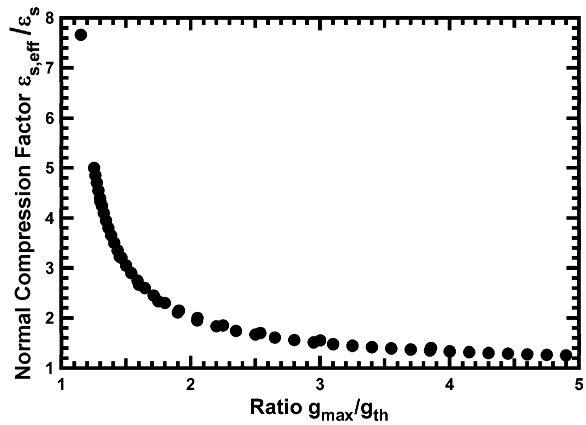


Fig. 2. Normalized compression factor as a function of $g_{\max}/g_{\rm th}$.

on high-frequency semiconductor current modulation that generates both amplitude (AM) and optical frequency (FM) modulation. The ratio of the FM over AM gives a direct measurement of the $\alpha_{\rm H}$-factor. This method has already demonstrated that an $\alpha_{\rm H}$-factor as high as 57 can be obtained in QD devices [23].

The aim of this study is to investigate the influence of gain compression and its consequence on the above threshold $\alpha_{\rm H}$-factor of the 1.3-$\mu$m InAs–GaAs QD laser published in [23]. After deriving the gain compression coefficient from relaxation frequency measurements, a theoretical approach including an effective gain compression factor is used. The model explains the dependence of the $\alpha_{\rm H}$-factor with the injected current, the occurrence of the giant $\alpha_{\rm H}$-factor, and even its collapse down to negative values due to the transition from the ground state (GS) to the excited state (ES). The increase of the $\alpha_{\rm H}$-factor with current is attributed to the enhancement of the gain compression through the gain saturation with the carrier density in QDs. As shown in the paper, a qualitative agreement with AM/FM experiments is obtained. Thus, taking into account the ES in the dots as well as the continuum states in the quantum wells explains the degradation of the GS $\alpha_{\rm H}$-factor [24]. To the best of our knowledge, we believe that such a comparison between calculations and AM/FM measurements on the above threshold $\alpha_{\rm H}$-factor has not been reported yet. Thus, these results are of first importance because they point out the role of gain compression and that a larger maximum gain is required for getting a lower $\alpha_{\rm H}$-factor in a real laser. This can be critical for the realization of chirpless devices as well as for isolator-free transmission under direct modulation and without transmission dispersion penalty.

## II. Device Description

The laser under study was grown by molecular beam epitaxy (MBE) [23]. The active region is made of three layers of self-assembled InAs QDs covered by a 5-nm InGaAs QW and separated from each other by a 40-nm GaAs space layer.

The dot density per stack is about $3 \times 10^{10}$ cm$^{-2}$. The laser cavity is clad by 1.5-$\mu$m $Al_{0.7}Ga_{0.3}As$ layers. The device is a 1.950-mm-long Fabry–Perot ridge waveguide laser (RWG) with 3-$\mu$m-wide stripe. Coated front and rear facet reflectivities are equal, respectively, to 79% and 93% at 1.3 $\mu$m. In Fig. 1, the light current characteristic $L(I)$ measured at room temperature is depicted. The threshold current leading to a GS emission is 13 mA and the external differential efficiency is about 0.02 W/A. The GS and ES transitions emit, respectively, at 1290 and 1210 nm [23]. Let us note that the ES lasing emission occurs for a threshold current equal to 220 mA at room temperature. The QD size distribution as well as the Fabry–Perot cavity leads to a widely multimode emission as shown in [23].

## III. Evaluation of Gain Compression

Measuring the frequency response as a function of the output power is a common method to evaluate gain compression in semiconductor lasers. In the case of the QD laser, it has been shown that effects of gain compression are more important than those measured on quantum-well devices [24], [25]. In order to explain this phenomenon, a modified nonlinear gain coefficient has been introduced leading to a new expression for the relaxation frequency under strong gain saturation such as [24]

$$f_r^2 = \frac{v_g a S}{4\pi^2 \tau_p (1+\varepsilon_S S)} \approx \frac{v_g a_0 S}{4\pi^2 \tau_p (1+\varepsilon_{S\text{eff}} S)} \tag{2}$$

where $v_g$ is the group velocity, $a$ is the differential gain, $a_0$ is the differential gain at threshold (unsaturated value), $S$ is the photon density, $\tau_p$ is the photon lifetime, $\varepsilon_S$ is the gain compression factor related to the photon density, and $\varepsilon_{S\text{eff}}$ is the effective gain compression factor defined as follows:

$$\varepsilon_{S\text{eff}} = \varepsilon_S \frac{1}{1 - \frac{g_{\rm th}}{g_{\max}}} \tag{3}$$

where $g_{\rm th}$ is the gain at threshold and $g_{\max}$ is the maximum gain for GS lasing. Equation (3) indicates that the gain compression is enhanced due to gain saturation by a factor of $g_{\max}/(g_{\max} - g_{\rm th})$. In Fig. 2, the evolution of the normalized gain compression $\varepsilon_{S\text{eff}}/\varepsilon_S$ is plotted as a function of the ratio $g_{\max}/g_{\rm th}$.

This shows that the higher the ratio $g_{\max}/g_{\rm th}$ the lower the effects of gain compression. If $g_{\max} \gg g_{\rm th}$ the graph tends to an asymptote such that $\varepsilon_{S\text{eff}}/\varepsilon_S \rightarrow 1$. On the other hand, if $g_{\max} \rightarrow g_{\rm th}$, gain compression effects are strengthened: the ratio increases drastically and can even be extremely large if

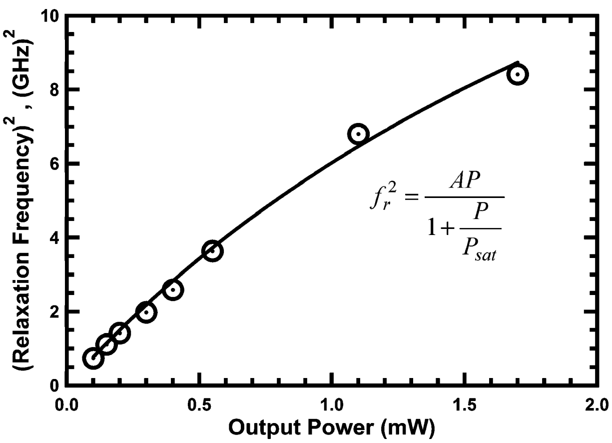


Fig. 3. Square of the resonance frequency versus the output power. The curve-fitting equation is shown in the inset and leads to $\mathrm{A} = 7.5 \pm 0.2$ (GHz)$^2$ mW$^{-1}$ and $\mathrm{P}_{\mathrm{sat}} = 3.3 \pm 0.3$ mW.

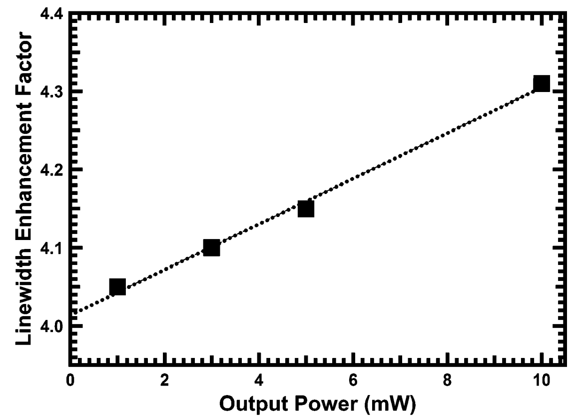


Fig. 4. Effective linewidth-enhancement factor $\alpha_{\mathrm{H}}$ as a function of the output power for the QW DFB laser.

not enough gain is provided within the structure ($g_{\max} \approx g_{\mathrm{th}}$). As an example, for the QD laser under study, $g_{\max}/g_{\mathrm{th}} \approx 2$, meaning that the effects of gain compression are doubled, causing critical degradation to the laser bandwidth. In order to extract the intrinsic properties of this InAs–Gas QD laser, microwave frequency properties have been investigated.

In Fig. 3, the square of the measured resonance frequency is plotted as function of the output power which is linked to the photon density through the relation $P = h\nu V v_g \alpha_m S$, where $\mathrm{h}\nu$ is the energy per photon, $V$ is the cavity volume, and $\alpha_m v_g$ is the energy loss through the mirrors where $\alpha_{\mathrm{m}}$ is the mirror loss. The experimental dependence of the relaxation oscillation frequency shows a deviation from the expected proportionality on the square root of the optical output power. As shown in the inset, a curve-fit based on (2) is used to express the gain compression in terms of a saturation power, $P_{\mathrm{sat}} \sim 3.3$ mW, where $\varepsilon_S S = \varepsilon_P P = P/P_{\mathrm{sat}}$ where $\varepsilon_P$ is the gain compression coefficient related to the output power $P$. This value means that at this level of output power, nonlinear effects start to be significant. Owing to the value of the saturated power $P_{\mathrm{sat}}$, the gain compression coefficient related to the output power is estimated to be $\varepsilon_P = 1/P_{\mathrm{sat}} \approx 0.3$ mW$^{-1}$. The maximum of the resonance frequency can be directly deduced from the curve-fitting as $\Omega_r = (AP_{\mathrm{sat}})^{1/2}$ and is expected to be ≈5 GHz (not shown in Fig. 3).

Taking into account the facet reflectivity as well as the modal volume of the laser, the order of magnitude for the gain compression factor $\varepsilon_S$ is in the range from $5 \times 10^{-15}$ cm$^3$ to $1 \times 10^{-16}$ cm$^3$. This value is in good agreement with those already reported for QD lasers [25], [26] on GaAs, remaining much larger than those measured on QW lasers (typically around $10^{-17}$ cm$^3$) [27].

## IV. On the Above-Threshold $\alpha_{\mathrm{H}}$-Factor

In QW lasers, which are made from a homogeneously broadened gain medium, the carrier density and distribution are clamped at threshold. As a result, the change of the $\alpha_{\mathrm{H}}$-factor is due to the decrease of the differential gain from gain compression and can be written according to the relation

$$\alpha_H = \alpha_{\mathrm{HO}}(1 + \varepsilon_P P) \tag{4}$$

where $\alpha_{\mathrm{HO}}$ is the linewidth-enhancement factor at threshold. Since the carrier distribution is clamped, $\alpha_{\mathrm{HO}}$ itself does not change as the output power increases. As an example, Fig. 4 shows the measured linewidth-enhancement factor versus the output power for a QW DFB laser. Black squares correspond to experimental data. As described by (4), the effective $\alpha_{\mathrm{H}}$-factor linearly increases with the output power. By curved-fitting those data, the $\alpha_{\mathrm{H}}$-factor at threshold is found to be around 4 while the gain compression coefficient equals $\sim 0.03\mathrm{mW}^{-1}$. Compared to QD lasers, such a value of the gain compression coefficient is much lower since the enhancement of the effective $\alpha_{\mathrm{H}}$-factor is not significant over the range of power.

In QD lasers, the carrier density and distribution are not clearly clamped at threshold because the inhomogeneous broadening gain is more predominant. Indeed, the lasing wavelength can switch from GS to ES as the current injection increases, meaning that a carrier accumulation occurs in the ES even though lasing in the GS is still occurring. The filling of the ES inevitably increases the $\alpha_{\mathrm{H}}$-factor of the GS, introducing an additional dependence with the injected current. Thus taking into account the gain variation at the GS and at the ES, the index change at the GS wavelength can be written as follows:

$$\delta n = \sum_{k=g,e} \alpha_k \delta g_k \tag{5}$$

where $k = g, e$ are the indices of summation for GS and ES, respectively. Equation (5) leads to

$$\delta n = \left(\alpha_e \frac{a_e}{a_g} + \alpha_g\right) \delta g_g \equiv \alpha_H \delta g. \tag{6}$$

In (6), $\delta g$ and $\delta n$ are the changes of the gain and refractive index at the GS, respectively, $\alpha_H$ is the linewidth enhancement factor actually measured in the device, $a_e$ and $a_g$ are the differential gains at the ES and at the GS, respectively, $\alpha_e$ describes the change of the GS index caused by the ES gain, and $\alpha_g$ is related to the GS index change caused by the GS gain variation. When the laser operates above threshold, $\alpha_g$ keeps increasing according to (4), as previously shown for the case of QW devices. Let us note that the differential gain at GS, $a_g$, can also be simply expressed as a function of the gain compression coefficient as well as $g_{\max}$ and $g_{\mathrm{th}}$. Indeed, it has been shown in [25] that the gain saturation in a QD media can be described by the following equation:

$$g_g = g_{\max}\left[1 - e^{-ln(2)\left(\frac{N}{N_{\mathrm{tr}}}-1\right)}\right] \quad (7)$$

where $N$ is the carrier density and $N_{\mathrm{tr}}$ is the transparency carrier density. When the laser operates above threshold, the differential gain for the GS lasing is defined as follows:

$$a_g = \frac{dg_g}{dN} = \frac{ln(2)}{N_{\mathrm{tr}}}(g_{\max} - g_g) \quad (8)$$

where $g_g = g_{\mathrm{th}}(1 + \varepsilon_P P)$ is the uncompressed material gain increasing with the output power. Equation (8) leads to

$$a_g = a_0\left(1 - \frac{g_{\mathrm{th}}}{g_{\max} - g_{\mathrm{th}}}\varepsilon_P P\right) = a_0\left(1 - \frac{g_{\mathrm{th}}}{g_{\max} - g_{th}}\varepsilon_S S\right) \quad (9)$$

where $a_0$ is the differential gain at threshold. Then, using (4), (6), and (9), the linewidth-enhancement factor can be written as

$$\alpha_H(P) = \alpha_g(1 + \varepsilon_P P) + \frac{\alpha_0}{1 - \frac{g_{th}}{g_{\max} - g_{\mathrm{th}}}\varepsilon_P P} \quad (10)$$

where $\alpha_0 = \alpha_e(a_e/a_0)$. The first term in (10) denotes the gain compression effect at the GS (similar to QWs) while the second is the contribution from the carrier filling in the ES that is related to the gain saturation in the GS. For the case of strong gain saturation, (10) can be reduced to

$$\alpha_H(P) = \frac{\alpha_0}{1 - \frac{g_{\mathrm{th}}}{g_{\max} - g_{\mathrm{th}}}\varepsilon_P P}. \quad (11)$$

In Fig. 5, the normalized linewidth enhancement factor $\alpha_{\mathrm{H}}/\alpha_0$ is calculated through (11) and reported in the $(X, Y)$ plane with $X = P/P_{\mathrm{sat}}$ and $Y = g_{\max}/g_{\mathrm{th}}$. This picture acts as a stability map that simply shows that a larger maximum gain is absolutely required for a lower and stable $\alpha_H/\alpha_0$ ratio. For instance, let us consider the situation for which $g_{\max} = 3g_{\mathrm{th}}$: at low output powers, i.e., $P < P_{\mathrm{sat}}$, the normalized $\alpha_{\mathrm{H}}$-factor remains constant ($\alpha_H/\alpha_0 \sim 3$) since gain compression is negligible. On the other hand, as soon as the output power approaches $P_{\mathrm{sat}}$ and goes beyond, the ratio $\alpha_H/\alpha_0$ is increased. Gain compression effects lead to an enhancement of the normalized $\alpha_H$-factor, which can go up to 10 for $P \approx 2P_{\mathrm{sat}}$ level of injection for which the ES occurs.

On the other hand, assuming $g_{\max} = 5g_{\mathrm{th}}$, Fig. 5 shows that the effects of gain compression are significantly attenuated since the ratio $\alpha_H/\alpha_0$ remains almost constant over a wider range of output power. The level at which gain compression starts being critical is now shifted to $P \approx 3P_{\mathrm{sat}}$ instead of $P \approx P_{\mathrm{sat}}$. Let us also stress that, at a certain level of injection, the normalized GS $\alpha_{\mathrm{H}}$-factor can even become negative. This effect has already been experimentally reported in [23] and they occur when the GS gain collapses, e.g., when ES lasing wavelength occurs.

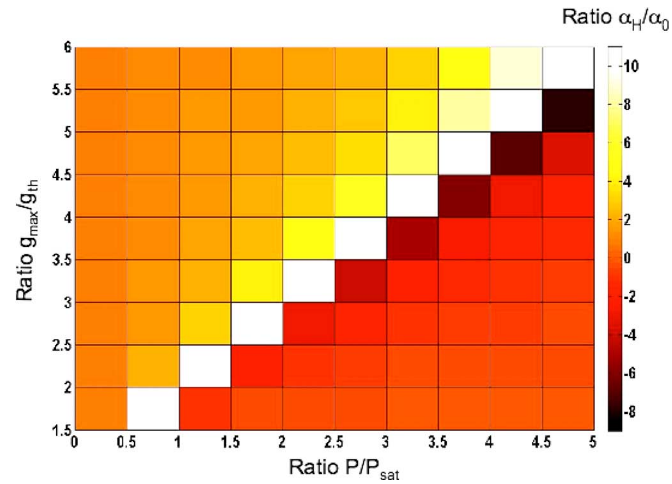


Fig. 5. Stability map based on the normalized linewidth-enhancement factor $\alpha_H/\alpha_0$ in the $(P/P_{\mathrm{sat}}, g_{\max}/g_{\mathrm{th}})$ plane.

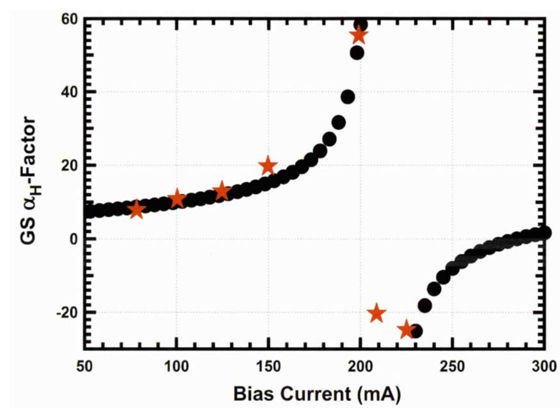


Fig. 6. Calculated GS $\alpha_{\mathrm{H}}$-factor versus the bias current (black dots). Superimposed red stars correspond to experimental data from [23].

In Fig. 6, the calculated GS $\alpha_{\mathrm{H}}$-factor (black dots) of the QD laser under study is depicted as a function of the bias current. Red stars superimposed correspond to data measurements from [23], which have been obtained via the AM/FM technique. This method consists of an interferometric method: the output optical signal from the laser operated under small-signal direct modulation is filtered in a 0.2-nm resolution monochromator and sent in a tunable Mach–Zehnder interferometer. From separate measurements on opposite slopes of the interferometer transfer function, phase and amplitude deviations are extracted against the modulating frequency, in the 50-MHz–20-GHz range [28]. The LEF is given by the phase to amplitude responses ratio at the highest frequencies, in the limits of the device modulation bandwidth

Thus, a qualitative agreement between simulations and measurements is obtained. As expected, the GS $\alpha_{\mathrm{H}}$-factor increases with the injected current due to the filling of the excited states as well as carrier filling of the nonlasing states (higher lying energy levels such as the wetting layer), which results in a differential gain reduction above threshold. Although the $\alpha_H$-factor is enhanced at lower output powers, this increase stays relatively limited until the bias current remains lower than 150 mA, e.g., such that as $P < P_{sat}$. Beyond that, compression effects start being significant and the $\alpha_H$-factor reaches a maximum of 57 at 200 mA before collapsing to negative values. As previously mentioned, the collapse in the $\alpha_H$-factor is attributed to the occurrence of the ES as well as to the complete filling of the available GS states. In other words, as the ES stimulated emission requires more carriers, it affects the carrier density in the GS, which is significantly reduced. As a result, the GS $\alpha_H$-factor variations from 57 down to $-30$ may be explained through a modification of the carrier dynamics such as the carrier transport time including the capture into the GS. This last parameter affects the modulation properties of high-speed lasers via a modification of the differential gain [25]. As a conclusion, these results are of first importance because they show that the $\alpha_H$-factor can be controlled by properly choosing the ratio $g_{max}/g_{th}$: the lower $g_{th}$, the higher $g_{max}$, the smaller the linewidth-enhancement factor. A high maximum gain can be obtained by optimizing the number of QD layers in the laser structure while gain at threshold is directly linked to the internal and mirror losses. Both $g_{th}$ and $g_{max}$ should be considered simultaneously so as to properly design a laser with a high differential gain and limited gain compression effects. The $g_{max}/g_{th}$ ratio is definitely the key-point in order to obtain a lower $\alpha_H$-factor for direct modulation in QD lasers.

## V. Conclusion

The effects of the nonlinear gain on a 1.3-$\mu$m InAs–GaAs QD laser have been investigated. Owing to the relaxation frequency dependence with the output power, the compression factor has been determined and estimated to be significantly larger than in QW devices, as previously observed. Based on a theoretical approach including nonlinear gain, it has been found that gain compression is systematically strengthened in QD devices because of the gain saturation with carrier density (by a factor of 2 in the laser under study). Regarding the $\alpha_H$-factor, a qualitative analysis has been performed based on an analytical model taking into account the filling both in the GS and in the ES. A good agreement with measurements published in the literature has been obtained: the model reproduces the increase of the $\alpha_H$-factor with current, the giant value reported close to the transition GS-ES as well as the collapse down to negative values after the transition. To the best of our knowledge, this is the first time that such behaviour is reported in the literature. Results also show that the optimization of the ratio $g_{max}/g_{th}$ is the key point for the realization of state-of-the-art QD devices. A higher maximum gain is definitely required for getting a lower $\alpha_H$-factor, which is really decisive for the realization of chirpless devices and isolator-free transmission.

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