The above-threshold linewidth enhancement factor of silicon-based quantum dot lasers

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Abstract: The spectral dependence of the linewidth enhancement factor of silicon based InAs/GaAs quantum dot lasers is investigated above the threshold by using a phase modulation method. Low values of linewidth enhancement factor measured at twice the threshold are reported. Such results confirm the high quality of the quantum dot material.

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1. Introduction

Quantum dot (QD) lasers demonstrate excellent performance in terms of low threshold current, high temperature stability, high modulation rate, high feedback insensitivity, and low linewidth enhancement factor (LEF or α_H-factor). At the same time, the QD structure is insensitive to dislocations, making QD lasers on silicon strong candidates for silicon photonic integration. The α_H-factor is a very important parameter driving many fundamental properties such as the laser linewidth as well as the dynamical and nonlinear properties [1][2]. On the first hand, the amplified spontaneous emission (ASE) method is probably the most common technique to access the α_H-factor [1]. However, this method does not always correspond to an actual situation since it is strictly limited to the ASE regime. On the other hand, the optical injection locking gives above-threshold values of the α_H-factor but requires a low injection ratio to protect the laser from the master laser. Therefore, as it is quite difficult to properly injection-lock the laser, inaccurate results in the α_H-factor extraction are observed [3]. Finally, the interferometric method relying on a Mach-Zehnder interferometer produces highly reliable data of the α_H-factor values, however it can only be applied to single-mode lasers [4]. In this study, a phase modulation (PM) method is considered instead and applied to a multimode laser [5]. The sinusoidal optical PM signal is used to obtain the information of the longitudinal modes so as to extract the above-threshold α_H-factor. Recently, the same method was applied to quantum cascade lasers to analyze the role the α_H-factor has in the frequency comb dynamics [6]. In this paper, a silicon based Fabry–Perot (FP) QD laser is considered. The effect of different modulation frequencies is studied. Lastly, the α_H-factor obtained from the ASE method is used as a reference to better compare the increase of the α_H from below to above threshold.

2. Experiments and Results

The silicon based InAs/GaAs Fabry–Perot (FP) laser consists of five p-doped QD layers. The density of QD is as high as 6.5×10^{10} cm^{-2}. The laser is 1.35 mm long with a 3.5 µm wide ridge waveguide. The reflectivity of both facets is 32%. The QD laser is kept at a constant operating temperature of 30 °C. The threshold current I_{th} is 36 mA. Fig. 1 presents the experimental setup used for performing the optical phase modulation. At the beginning, the tunable RF signal (f_m) is divided into two channels by RF Power Splitter (RFPS), modulating the QD laser and phase modulator (PM) at the same time. The sin wave signal applied to the QD laser could be controlled by RF variable attenuator to keep it within the small signal modulation. In addition, the bias tee (BT) allows the QD laser to be pumped by direct current. The laser beam passes through an optical delay line (ODL) before entering the phase modulator to control the delay between the optical and electrical signal at the input of the phase modulator. Finally, the modulated signal is sent to an optical spectrum analyzer (OSA). In this method, four optical spectra corresponding to four different delays ($1/(4f_m)$) are needed to extract the linewidth enhancement factor. The bias current of laser is set to twice the threshold (72 mA) in this setup.

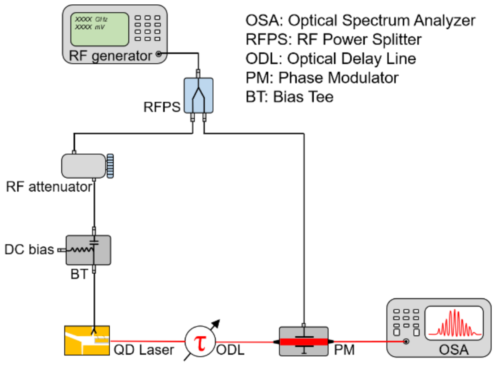

Figure 1. Schematics of the experimental set-up of optical phase modulation (PM) technique.

The frequency dependence of the amplitude phase coupling reads as $\alpha_m = \alpha_H[1+(f_c/f_m)^2]^{1/2}$ with f_c the corner frequency and f_m the modulation frequency. Therefore, we use the PM method to obtain the spectral dependent α_m of different modulation frequencies from 6.5 GHz to 8.5 GHz. (Fig. 2(a)). According to the curve-fitting, the corner frequency f_c =21.35 GHz >> f_m which means that $\alpha_m \sim \alpha_H$ so we can use this expression to get the α_H-factor. Fig. 2(b) depicts the optical spectrum and the corresponding α_H-factor extracted for 18 longitudinal modes near the gain peak. We demonstrate very low values of α_H-factor at twice the threshold current in epitaxial QD lasers with values between ~1.0 and ~1.6 across the optical spectrum. We also compare the α_H-factor obtained by the ASE method with the α_H-factor obtained by the PM method (Fig. 2(c)). The α_H-factor at twice the threshold current is found larger than the below-threshold one. This effect is due to the gain compression and from the contribution of the off-resonance energy states. Further work will involve rate equations to model the α_H-factor and the subsequent parameters when the QD lasers operates under small signal modulation.

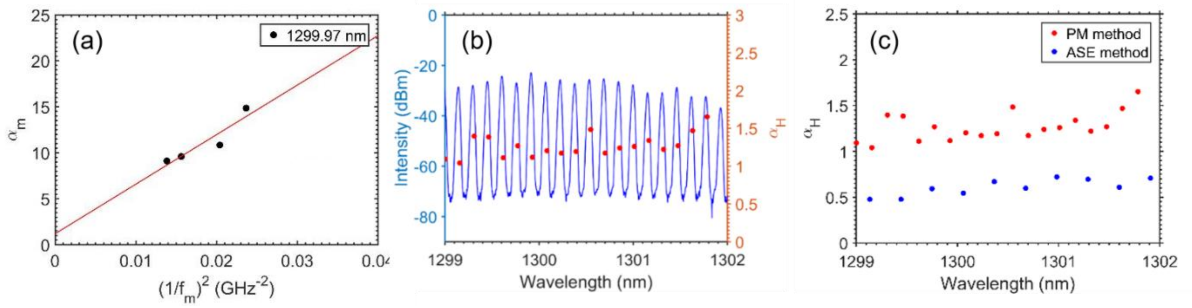

Figure 2. (a) Modulation frequency dependent α_m-factor, (b) spectral dependence of the α_H-factor, and (c) comparison between the below-threshold α_H-factor (blue) and the above-threshold one (red).

3. Conclusions

The very low values of the above-threshold α_H-factor obtained from the PM method confirm the high quality of the material. This work has important implications for silicon integration technology. We will then further investigate the mechanism by which the α_H-factor varies above and below the threshold current.

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