Investigation of the Chromatic Dispersion in Two-Section InAs/GaAs Quantum-Dot Lasers

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***Abstract*— We present the measurements of the dispersion of InAs/GaAs quantum-dot lasers emitting at 1230 nm (ground state) and 1160 nm (excited state) from the analysis of their subthreshold emission spectra. Measurements from devices with various lengths allow us to deduce that the group velocity dispersion is as high as 2270 fs^2mm^{-1} and is mainly due to the dispersion of bulk GaAs. The gain-induced dispersion varies with the injected current at a rate of $\simeq -2$ $fs^2mA^{-1}mm^{-1}$, whereas the effect of a saturable absorber on the dispersion is found to be negligible. These results suggest that the implementation of integrated dispersion compensation could significantly reduce the pulse duration of these lasers in mode-locked regime and lead to an enhancement of the formation of optical frequency combs in these devices.**

***Index Terms*— Semiconductor lasers, quantum dots, mode locked lasers, dispersion curves.**

I. Introduction

THE generation of light pulses at GHz repetition rates has opened up new possibilities in various technological f elds such as telecommunications or spectroscopy. In particular, the use of mode-locked semiconductor lasers can offer signif cant advantages due to their compactness and robustness. Semiconductor lasers can be actively mode-locked by modulating the amplitude of the light inside the optical cavity at a high repetition rate. Alternatively, a saturable absorber can be integrated in the laser cavity in order to passively lock the laser optical modes. In particular, quantum-dot (QD) lasers can be passively mode-locked thanks to their ultra fast gain dynamics [1], [2] using a two-section device scheme [3]–[5].

When the back section of the device (see Fig. 1) is biased with a reverse dc voltage, it acts as a saturable absorber. This means that any large optical burst generated inside the laser cavity will spontaneously shorten and lead to mode-locking of the laser emission. Another mechanism that can lead to passive mode-locking in single section Fabry-Pérot semiconductor lasers is four-wave mixing. A high gain non linearity can lead to coupling of the longitudinal optical modes. Passive mode-locking of single section Fabry-Pérot lasers was reported in quantum well lasers [6], QD lasers [7], quantum dash lasers [8] as well as in quantum cascade lasers [9]. In quantum cascade lasers intra-cavity dispersion compensation can lead to a strong enhancement of this phase locking mechanism [10], [11] but such work has not been done for QD lasers yet.

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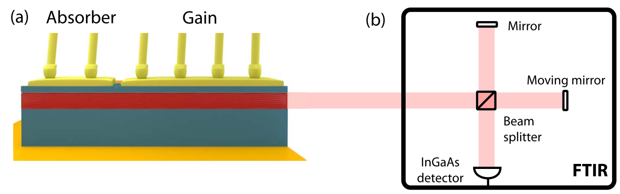

Fig. 1. (a) Schematic of the measured devices. These include an electrically isolated saturable absorber section. (b) Schematic of the experimental setup. A FTIR including a CaF_2 beamsplitter and an InGaAs detector is used.

II. Experimental Results

It was observed that the pulses generated from mode-locked lasers are linearly chirped, their group delay dispersion (GDD) can reach up to a few ps^2 and can vary under modif cation of the absorber bias conditions [12]. This suggests that the pulse dispersion is a property of the comb operation regimes and is not equal to the chromatic dispersion [8]. Therefore, in order to retrieve the chromatic dispersion of the devices we use a technique based on an analysis of the subthreshold emission spectrum by Fourier transforms [13]. This method was already applied to AlGaInP-based interband laser diodes and to mid-infrared quantum cascade lasers [10], [13]. The analysis presented here was performed on self-organized InAs/GaAs QD lasers similar to [4] and emitting at 1230 nm (ground state) and 1160 nm (excited state). The active region incorporated 10 non-identical InAs QD layers. The 643 nm thick GaAs waveguide core was placed in between 1520 nm thick $Al_{0.15}Ga_{0.85}As$ cladding layers (Si doped $n = 10^{17}$ cm^{-3} and C doped $p = 10^{18}$ cm^{-3}). The lasers had two-sections [2] and included an integrated saturable absorber at the back of the device. A schematic of the devices is displayed in Fig. 1 (a).

A 2 mm long two-section laser chip with a 6 μm wide ridge waveguide with a 0.5 mm long electrically isolated saturable absorber section was cleaved. The front and back facets of the laser chips were anti-reflectio (∼2%) and

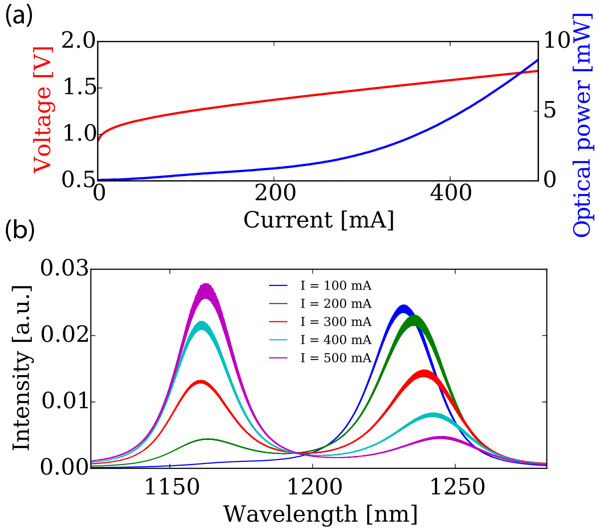

Fig. 2. (a) Light, current, voltage curve of the device was measured by injecting current homogeneously into the laser. (b) Spectra measured for currents ranging from 100 mA up to 500 mA by steps of 100 mA.

high-reflection (∼99%) coated, respectively. The device was mounted episide up on a copper submount and a Peltier cooler was used to maintain a constant operating temperature of 25 °C. The device was driven in continuous wave operation. The light- and voltage-current characteristics of the device were measured by injecting current homogeneously into both sections. The resulting curves are displayed in Fig. 2 (a). The light-current characteristic has the exponential form that is expected for subthreshold regime. The output beam was then directed toward the entrance of a Fourier transform interferometer (FTIR, Fig. 1 (b)), which contains a CaF_2 beamsplitter and an InGaAs detector. Interferograms were acquired for currents ranging from 100 mA up to 500 mA by steps of 100 mA. The computed spectra displayed in Fig. 2 (b) confirm that the device stays below threshold on the whole dynamic range. By increasing the current, the ground and the excited states are successively populated and the transitions are redshifted.

Since the device is operated below threshold, the interferograms contain a series of harmonic peaks with an exponentially decaying envelope which are due to the successive reflections of the luminescence inside the Fabry-Pérot cavity [13]. The centerburst (W_0 (d), Fig. 3 (a)) is measured at zero path difference. The first sidelobe (W_1 (d) Fig. 3 (b)) is measured at a delay corresponding to the distance $d = 2n_{eff}L$ where L is the length of the device and n_{eff} is the effective refractive index of the guided optical mode. The sidelobe contains information about the light that has travelled one round-trip inside the cavity. The dispersion of the laser cavity can therefore be retrieved by computing the Fourier transform of the sidelobe [13]. The phase spectrum, the group delay τ_g and the GDD of the excited state at a heatsink temperature of 25 °C and an injection current of 500 mA are displayed in Fig. 3 (c), (d) and (e) respectively. A large linear dispersion of the group delay is observed which agrees well with the literature [14]. A GDD of 9160 fs^2 is deduced at 1160 nm.

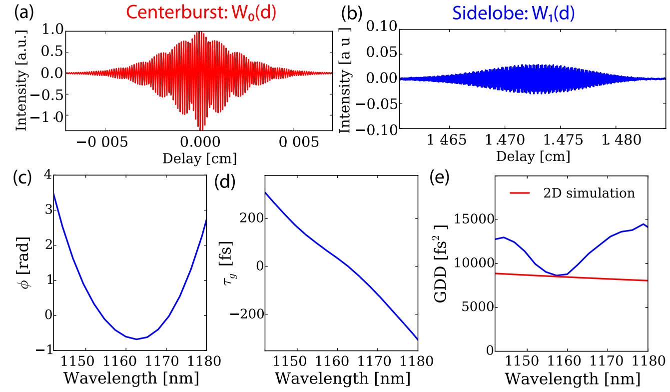

Fig. 3. At a heatsink temperature of 25 °C and an injection current of 500 mA: (a) Centerburst, (b) first sidelobe, (c) phase spectrum, (d) group delay τ_g, (e) measured GDD (blue curve). Simulated GDD for the waveguide including materials dispersion (red curve).

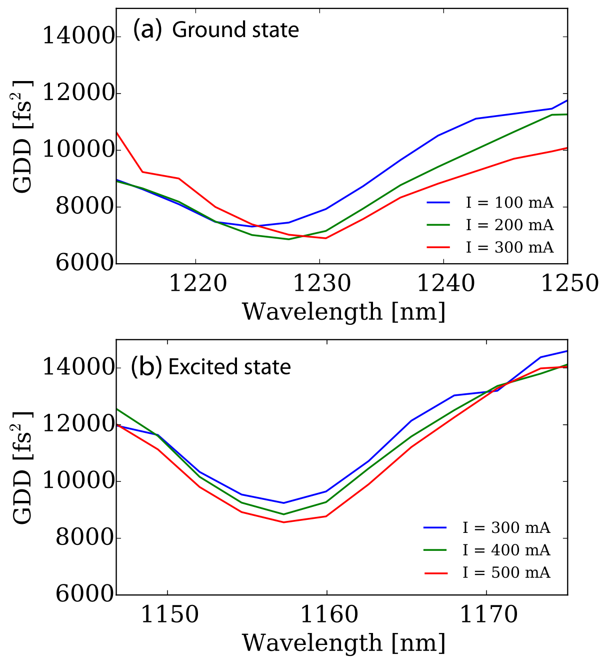

Fig. 4. The group delay dispersion was deduced for both the ground (a) and excited states (b).

We computed the dispersion of the fundamental mode of the waveguide in two dimensions using a finite elements method and including the dispersion of the materials computed from Pikhtin and Yas'kov formula [15] using the parameters given in [16] and obtained a GDD of 8170 fs^2. The result is shown in Fig. 3 (e) (red curve). The waveguide dispersion was also computed without taking into account the material dispersion and a value of 20 fs^2 was deduced. This shows that the main contribution to the GDD is the dispersion of bulk GaAs whereas the spectral shape of the measured GDD suggests that the gain induced GDD is non negligible.

In order to estimate the current dependent dispersion, the GDD was computed from 100 mA to 300 mA for the ground state and from 300 mA to 500 mA for the excited state. The spectra are displayed on Fig. 4 (a) and (b) respectively. The GDD for both transitions decreases with current at a rate

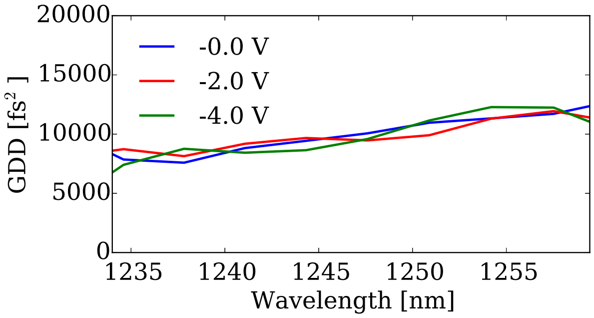

Fig. 5. The group delay dispersion spectra of the ground state for a current injection of 300 mA in the gain section and a reverse bias of 0, 2 and 4 V.

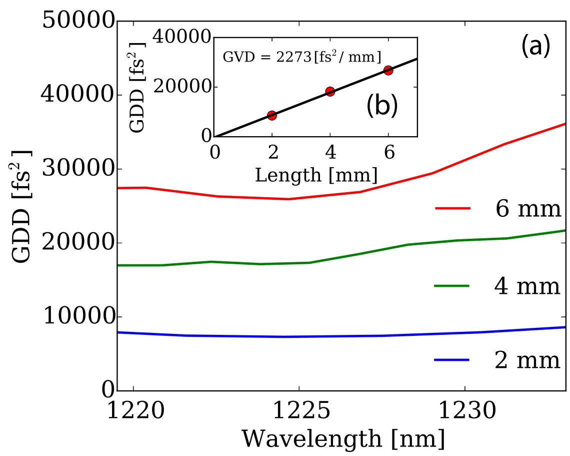

Fig. 6. (a) The group delay dispersion spectra of the ground state for a bias current of 100 mA is displayed for all devices. (b) A clear linear relationship is obtained and a value of 2270 $\text{fs}^2\text{mm}^{-1}$ is deduced for the group velocity dispersion of the ground state.

of $\simeq -2$ $\text{fs}^2\text{mA}^{-1}\text{mm}^{-1}$. This shows that the gain induced dispersion is non-negligible.

The effect of the absorber on the dispersion was therefore analysed as well. A constant current of 300 mA was f rst injected in the gain section and the bias applied to the absorber was successively varied from 0 V to -4 V. When the reverse bias was applied the signal from the excited state was too low to deduce its GDD. The GDD spectra of the ground state are displayed in Fig. 5. The GDD stays constant for the different biases. This shows that no intra-cavity gain induced dispersion compensation effect is induced by the absorber and conf rms that the inf uence of the absorber on the pulses dispersion is indeed due to its operation as saturable absorber.

In order to deduce the group velocity dispersion, a 6 mm and a 4 mm long two-section laser chips from the same InAs/GaAs QD structure were measured in the same experimental conditions. Both devices have a 6 μm wide ridge waveguide and an absorption-to-gain section length ratio of 1:3. The front and back facets of the laser chips were anti-reflectio (∼2%) and high-ref ection (∼99%) coated, respectively. The group delay dispersion spectra of the ground state was measured for all devices with a homogeneous bias current of 100 mA. It would be favourable to compare measurements performed at an equal current density. However, for high currents the longer devices operate above threshold and for low currents the shorter device luminescence emitted is too low in order to resolve the dispersion spectrum. Therefore, in this analysis, we neglect the variation of the dispersion due to the different pumping levels. The results are displayed in Fig. 6 (a). As expected, the GDD is proportional to the length of the device. The group delay dispersion at 1225 nm is also displayed as a function of the device length in Fig. 6 (b). A clear linear relationship is obtained and a value of 2270 $\text{fs}^2\text{mm}^{-1}$ can be deduced for the group velocity dispersion of the ground state.

III. Conclusion

To conclude, in this letter we have analysed the chromatic dispersion of InAs/GaAs QD lasers by measuring subthreshold luminescence spectra under a homogeneous bias or applying a forward bias to the gain section and a reverse bias to the saturable absorber section. These measurements allow to deduce that the main contribution to the GDD is the dispersion of bulk GaAs and the group velocity dispersion of the ground state is as high as 2270 $\text{fs}^2\text{mm}^{-1}$. However, the gain induced dispersion is non negligible and varies with the injected current at a rate of $\simeq -2$ $\text{fs}^2\text{mA}^{-1}\text{mm}^{-1}$ whereas the GDD stays constant when the absorber bias is varied. These results suggest that the implementation of intra-cavity dispersion compensation by means of an external cavity [17], a Gires-Tournois coating [10] or by waveguide engineering [11] could reduce the pulse duration of these lasers in the mode-locked regime to the level of a few hundreds fs [2]. These investigations will be the subject of future works.

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