Dynamic properties of InAs/InP (311)B quantum dot Fabry–Perot lasers emitting at 1.52 μm

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(Received 30 April 2008; accepted 18 June 2008; published online 14 July 2008)

Dynamic properties of truly three-dimensional-confined InAs/InP quantum dot (QD) lasers obtained by molecular beam epitaxy growth on a (311)B oriented substrate are reported. The relative intensity noise and small signal modulation bandwidth experiments evidence maximum relaxation frequency of 3.8 GHz with a clear relaxation oscillation peak, indicating less damping than InAs/GaAs QD lasers. The Henry factor amounts to ~1.8 below threshold and increases to ~6 above threshold, which is attributed to band filling of the thick wetting layer. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2957479]

Quantum dot (QD) based lasers have raised a lot of interest over the last decade since the early theoretical predictions of unique properties arising from three-dimensional carrier confinement.[1] Intense research in the growth of self-assembled QDs in the Stranski–Krastanov regime has hence allowed studies of these atomiclike nanostructures. Potential applications in fiber telecommunication pushed forward the development of long wavelength QD lasers both at 1.3 μm on GaAs substrate and on InP substrate for 1.55 μm applications. Indeed, low cost uncooled and isolator-free directly modulated lasers are very attractive for local area and metropolitan area networks. Subsequently, much effort has been devoted to the development of InAs/GaAs QDs with the demonstration of superior performances compared to that of QW based lasers. Unprecedented properties such as ultralow threshold current,[2] high characteristic temperature,[3] and increased tolerance to optical feedback[4] have readily been demonstrated. Moreover, error free 10 Gb/s data modulation of QD lasers emitting at 1.3 μm was reported, which shows that such sources should be ready for deployment.[5] For long-haul applications, lasers emitting at 1.55 μm are desirable as the emission wavelength correspond to the lowest attenuation of silica based optical fibers and to the amplification band of erbium doped fiber optical amplifiers. However, the optical fiber chromatic dispersion induces penalty for data transmission at 1.55 μm. One unique theoretical property of QD lasers relates to the near zero Henry factor at the gain peak of the laser.[6] This is a fundamental characteristic as it should open the way for chirpless penalty free high bit rate data transmission. Growth using molecular beam epitaxy (MBE) on (100) InP generally leads to elongated dots or so-called quantum dashes.[7–9] However, these quasi-one-dimensional nanostructures exhibit a linewidth enhancement factor (LEF) that amounts to ~4–6,[9,10] similar to that of the best QW lasers. More recently, MBE growth[11] and metal-organic chemical vapor phase epitaxy[12,13] (MOVPE) have allowed the growth of truly three-dimensionally confined QDs on InP (100). No investigation of the LEF has ever been reported in this material system. An alternative approach, which relies on MBE growth on a specific InP (311)B orientation, has also allowed the formation of QDs with a high dot density of 10^{11} cm^{-2}.[14,15] A very low chirp of 0.01 nm was measured but no direct measurement of the Henry factor was reported.[14]

In this paper, we report on the microwave frequency properties—relaxation frequency and Henry factor—of narrow ridge single mode waveguide Fabry–Perot (FP) lasers processed from a five InAs/InP (311)B QD layer structure emitting on the ground state (GS) at 1.52 μm. In particular, the Henry factor amounts to ~1.8 below threshold while it increases up to ~6 just above threshold, which is attributed to band filling of the thick wetting layer.

The laser heterostructure has been grown by MBE on a (311)B *n*+-oriented InP substrate. The active region consists of five QD layers and a modal gain of 16 cm^{-1} has been extracted from this layer structure.[16] 3 μm wide ridge waveguide FP lasers were processed by a Cl_2-H_2 induced coupled plasma etching process.[17] Benzocyclobutene allows planarization of electrodes with a small parasitic capacitance compatible with 10 Gb/s operation. The investigated lasers have as-cleaved facets. Lasing is observed on the QD GS at 1.52 μm at room temperature in continuous wave (cw) for cavities as short as 1030 μm. When the temperature increases from 20 to 70 °C, the threshold current of a 1100 μm long FP laser increases from 41 to 117 mA (Fig. 1). A characteristic temperature of 49 K is extracted, comparable to that observed in InAs/InP QD lasers grown by MOVPE.[13] This is attributed to nonradiative Auger recombination that was measured to account for 90% of the total current at room temperature on a similar layer structure.[18] Emission on the QD GS in cw regime is observed up to 75 °C at 200 mA, indicating the absence of excited state (ES) contribution.

The LEF was then assessed at room temperature below and above threshold on the same device. The Henry factor is defined as $-4\pi/\lambda \times (\delta n/\delta N)/(\delta g/\delta N)$ and represents the variation in the real part of the refractive index change over the differential gain when the carrier density changes. The LEF was primarily assessed below threshold. Figure 2 depicts the measured net gain when the current is increased

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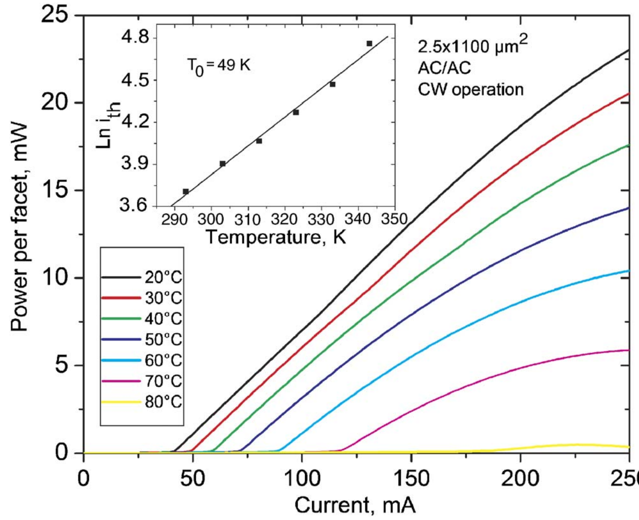

FIG. 1. (Color online) *L-I* characteristics of a 1100 μm long FP laser with as-cleaved facets for temperature from 20 to 80 °C in cw regime and characteristic temperature (inset).

from 26 to 41 mA in steps of 3 mA. The Henry factor α_H decreases with the current and amounts to 1.8 at the gain peak just below threshold (Fig. 2). As the differential gain decreases near threshold (Fig. 2), the decrease in the LEF is attributed to an almost vanishing refractive index change. The "material" LEF of InAs/InP (311)B QD lasers is smaller than that of earlier values of InAs/InP QDash lasers,[9,10] which is attributed to a smaller differential refractive index. We also performed measurement of the differential index and gain within the homogeneous linewidth of the QD population. A similar trend and comparable values are observed at 1517 and 1527 nm, although the α_H at the longer wavelength equals ~3.1 due to a lower differential gain. The evaluation of the "device" LEF above threshold is more relevant for telecommunication applications as it corresponds to a regime where sufficient optical power is available for data transmission. To determine the LEF, a high frequency current modulation technique was applied with a modulation frequency of 7 GHz.[19] The LEF is measured at the gain peak and it amounts to 6.8 at ~1522 nm just above threshold. A drastic increase in the LEF is indeed evidenced when the laser is

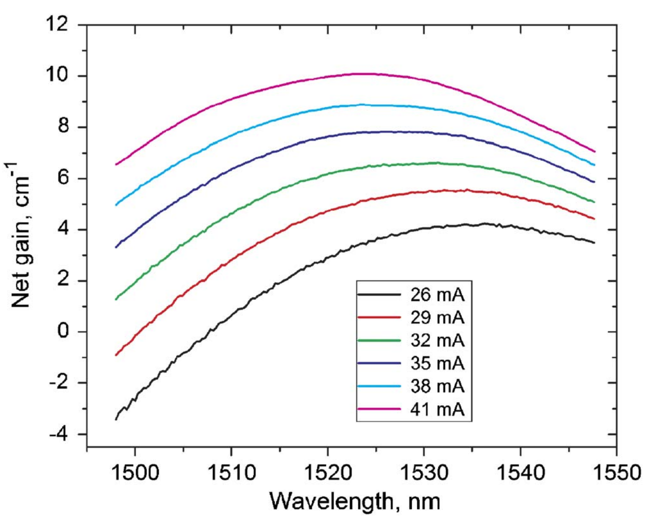

FIG. 2. (Color online) Net gain at 20 °C in cw regime of a 1100 μm long FP laser vs current below threshold.

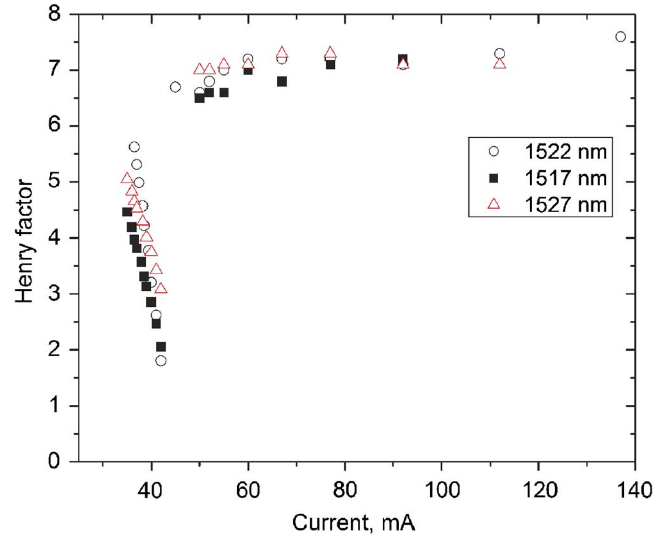

FIG. 3. (Color online) Henry factor below and above threshold of a 1100 μm long InAs/InP (311)B QD FP laser.

biased above threshold. This behavior is attributed to a plasma effect, similar to that invoked in InAs/GaAs QDs.[20] We believe that above threshold, the dot GS occupation probability is saturated.[20] This results in a significant band filling of the higher energy levels, i.e., the wetting layer (high degeneracy states) and the barrier/waveguide, that breaks the Gaussian-like symmetry of the gain spectrum. The Henry factor does not noticeably change with the bias current as it amounts to 7.7 at 137 mA. This behavior is comparable to what was earlier reported in quantum dash-in-a-well lasers.[9] Reduced nonlinear gain compression and the absence of ES emission at high injection current in InAs/InP (311)B QD lasers result in a smaller rate of decrease in the differential gain with the current density compared to five InAs/GaAs QD layer structures.[19] This explains why no divergence of the Henry factor is observed at high injection current, unlike InAs/GaAs QD lasers where it was attributed to incomplete gain clamping of the ES at the GS threshold gain.[19] The LEF was also measured on two other longitudinal modes at 1517 and 1527 nm (i.e., within the corresponding homogeneous linewidth): similar values of the LEF ~7 are obtained just above threshold and the LEF does not exhibit any significant dependence with the carrier density up to $2.5\times\mathbf{i}_{th}$. The LEF is thus constant over 10 nm within the homogeneous broadening of the QD ensemble population. Indeed, the high density of final states of the thick wetting layer favors the electron transition back to the wetting layer, which adversely affects the LEF.

Microwave frequency properties were investigated by means of relative intensity noise (RIN) measurements to extract the intrinsic properties of QD lasers. Figure 4 illustrates the evolution of the relaxation frequency versus the normalized current. The modulation efficiency equals 0.38 GHz/mA$^{1/2}$, lower than 0.63 GHz/mA$^{1/2}$ measured in standard five InAs/GaAs QD lasers.[19] The relaxation frequency f_r and the −3 dB bandwidth reach a maximum value of 3.8 and 4.8 GHz, respectively, at a 137 mA bias current. The evolution of the damping factor against the squared relaxation frequency leads to a K factor of 0.63 ns, implying a maximum intrinsic modulation bandwidth of 14.1 GHz. The gain compression is accountable for the lower experimental bandwidth, as evidenced in InAs/GaAs QD lasers.[21] Stack-

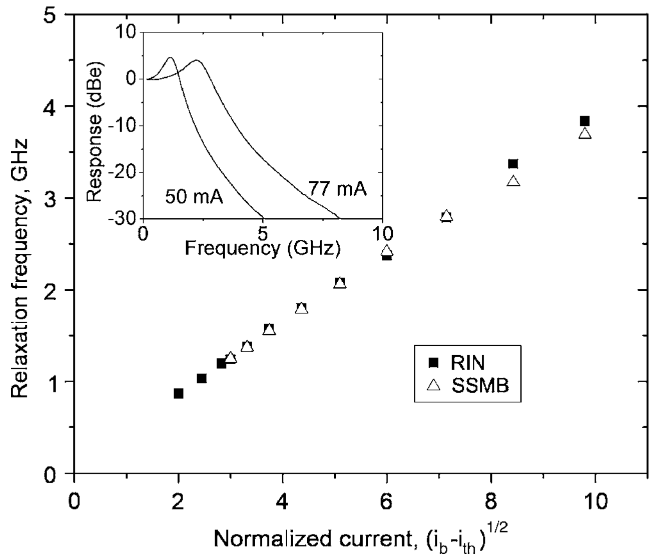

FIG. 4. Relaxation frequency measured from the RIN and small signal modulation bandwidth experiments vs the normalized current at 20 °C (inset: transfer function at 50 and 77 mA).

ing more QD layers into the active region should allow laser emission from shorter cavities compatible with 10 Gb/s direct modulation. As the *K* factor is about two times lower than that of standard InAs/GaAs QD layer structures,[21] the carrier dynamics in the conduction band of InAs/InP QDs may be governed by a different relaxation process. Small signal modulation bandwidth experiments were subsequently performed using a lightwave component analyzer. The extraction of the relaxation frequency versus the bias current shows nearly identical values to those obtained from RIN measurements, demonstrating a modulation efficiency of 0.36 GHz/mA$^{1/2}$. Taking into account a photon lifetime of 5.8 ps, a differential gain of 7.3×10^{-15} cm^2 is deduced. The evolution of the damping rate versus the current also allows the extraction of the nonlinear gain coefficient which equals 6.4×10^{-16} cm^3, lower than that of InAs/GaAs QDs lasers, where strong damping was attributed to carrier relaxation from the ES to the GS. Surprisingly, the peak of the relaxation oscillation is clearly distinguishable in the modulation transfer function of the InAs/InP (311)B QD lasers (inset Fig. 4). However, previous work evidenced suppression of relaxation oscillation peak in InAs/InP (311)B QD directly modulated lasers emitting at 1.64 μm.[14] This was attributed to spectral hole burning of isolated dots and we believe that the higher bandgap discontinuity in the conduction band (QD potential) was higher than that of our present device. Therefore, it is conjectured that no such carrier dynamics exist in InAs/InP (311)B QD lasers emitting on the GS at 1.52 μm as the energy transition between the wetting layer and the QD GS amounts to ~100 meV,[18] compared to ~300 meV for InAs/GaAs QDs emitting at 1.3 μm.

In conclusion, we thoroughly investigated the static and dynamic properties of InAs/InP (311)B QD lasers emitting on the GS at 1.52 μm. The Henry factor is found to be as low as 1.8 at the gain peak just below threshold and increases to about 6.6 above threshold but remains constant with the current. The rather high value is attributed to band filling of the thick wetting layer (high degeneracy states). The sole emission from the GS at high current and at a high temperature of 75 °C as well as a distinct relaxation oscillation peak in the frequency modulation response indicate the absence of phonon relaxation bottleneck originating from an ES.

This work has been supported by the EU EPIXnet Network of Excellence.

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