Intrinsic Dynamics of Quantum-Dash Lasers

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Abstract—Temperature-dependent intrinsic modulation response of InAs/InAlGaAs quantum-dash lasers was investigated by using pulse optical injection modulation to minimize the effects of parasitics and self-heating. Compared to typical quantum-well lasers, the quantum-dash lasers were found to have comparable differential gain but approximately twice the gain compression factor, probably due to carrier heating by free-carrier absorption, as opposed to stimulated transition. Therefore, the narrower modulation bandwidth of the quantum-dash lasers than that of quantum-well lasers was attributed to their higher gain compression factor. In addition, as expected, quantum-dash lasers with relatively long and uniform dashes exhibit higher temperature stability than quantum-well lasers. However, the lasers with relatively short and nonuniform dashes exhibit stronger temperature dependence, probably due to their higher surface-to-volume ratio and nonuniform dash sizes.

Index Terms—Differential gain, microwave modulation, optical modulation, quantum wells, quantum wires, semiconductor lasers.

I. INTRODUCTION

QUANTUM-DASH lasers are promising alternatives to quantum-well lasers in long-wavelength fiber-optic communication systems. Since their invention a decade ago [1], they have demonstrated many advantageous properties, including temperature stability [2], low noise [3], broad gain [4], and broad emission [5]. However, the modulation bandwidth of quantum-dash lasers is generally narrower than that of quantum-well lasers [6], [7].

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Similar to quantum-wire and quantum-dot lasers, quantum-dash lasers are more quantum confined than quantum-well lasers. The narrower modulation bandwidth of these highly quantum-confined lasers has been attributed to various limiting mechanisms, such as carrier capture, relaxation and escape [8], state filling [9], and inhomogeneous broadening [10]. To overcome these limitations, several approaches were proposed, including tunnel injection, *p*-doping of the active region [11], improved quantum-dash growth, and waveguide optimization [12]. These approaches improved the modulation bandwidth of quantum-dash lasers to greater than 10 GHz, but it still fell short of that of quantum-well lasers [13].

Further improvement of the modulation bandwidth of quantum-dash lasers hinges on understanding the effect of quantum confinement on dynamic laser properties, such as differential gain, gain compression factor, and temperature dependence. In particular, unlike previous studies [14], [15] on gain compression in quantum-dash lasers, this paper uses a pulse optical injection modulation technique to analyze the *intrinsic* dynamics of two types of quantum-dash lasers without self-heating or parasitic impedances. The first type of lasers has long dashes and resembles quantum-wire lasers, and the second type of lasers has short dashes and resembles quantum-dot lasers. Their intrinsic dynamics show that the differential gain of the quantum-dash lasers is comparable to that of a typical quantum-well laser, but the gain compression factor of the quantum-dash lasers is approximately twice that of the quantum-well laser. Therefore, the modulation bandwidth of the quantum-dash lasers appears to be mainly limited by the gain compression factor. In addition, while the long-dash laser exhibits superior temperature stability than the quantum-well laser, the short-dash laser exhibits comparable or even inferior temperature stability than the quantum-well laser. Since quantum-dot lasers have exhibited [16] superior temperature stability of the dynamic properties than quantum-well lasers, the inferior temperature stability of the present short-dash laser is attributed to its nonuniform dash sizes. These differences in modulation bandwidth and temperature dependence are analyzed in detail in the following.

II. LASER STRUCTURES

Table I lists the structures and fundamental properties of the three types of lasers used in the present investigation, which emphasizes qualitative comparison of intrinsic dynamics rather than quantitative comparison of performance merits. First, a quantum-well laser serves as the reference. Although the laser is not specially designed for high-speed performance, it exhibits typical characteristics of long-wavelength quantum-well lasers, such as a modulation efficiency of

TABLE I
STRUCTURES AND PROPERTIES OF THREE TYPES OF LASERS INVESTIGATED

Heterostructure	InGaAs/InGaAsP	InAs/InAlGaAs	
Quantum Confinement	Well	Long Dash	Short Dash
Number of Layers	5	5	4
Density	---	10^{10} cm^{-2}	
Size	5.5 nm	$300 \times 25 \times 5 \text{ nm}^3$	$(20-75) \times 18 \times 3 \text{ nm}^3$
Cavity Length	400 μm	400 μm	340 μm
Ridge Width	3 μm	4 μm	3 μm
Threshold Current	22 mA	44 mA	200 mA
Character. Temperature*	68 K	140 K	54 K
Emission Wavelength	1600 nm	1565 nm	1615 nm
Emission Bandwidth	<10 nm	~10 nm	>10 nm
Slope Efficiency	0.35 W/A	0.17 W/A	0.09 W/A
Internal Loss	17 cm^{-1}	14 cm^{-1}	18 cm^{-1}
Optical Confinement Factor	0.05	0.03	0.02
Active Volume	$3.3 \times 10^{-11} \text{ cm}^3$	$3.0 \times 10^{-11} \text{ cm}^3$	$1.2 \times 10^{-11} \text{ cm}^3$
Group Velocity	$8.3 \times 10^9 \text{ cm/s}$	$8.6 \times 10^9 \text{ cm/s}$	$8.2 \times 10^9 \text{ cm/s}$
Mirror Loss	28 cm^{-1}	25 cm^{-1}	33 cm^{-1}
Photon Lifetime	2.6 ps	3.0 ps	2.4 ps
Reference	[17]	[15]	[18]

*Characteristic temperature extracted from -50°C to 40°C .

$\sim 1 \text{ GHz/mA}^{1/2}$ and a K factor of $\sim 0.3 \text{ ns}$ (see Section IV). The laser is based on an InGaAs/InGaAsP heterostructure grown by metal-organic chemical vapor deposition lattice matched to an n -type (100) InP substrate. The undoped active region of the heterostructure consists of five 5.5-nm-thick $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ wells, which are separated by 12-nm-thick $\text{In}_{0.76}\text{Ga}_{0.24}\text{As}_{0.53}\text{P}_{0.47}$ barriers. Optical confinement is provided first by 50-nm-thick $\text{In}_{0.81}\text{Ga}_{0.19}\text{As}_{0.42}\text{P}_{0.58}$ layers, and then by 80-nm-thick $\text{In}_{0.90}\text{Ga}_{0.10}\text{As}_{0.23}\text{P}_{0.77}$ layers. The upper cladding is a 1.5- μm -thick InP layer doped with $7 \times 10^{17} \text{ cm}^{-3}$ of Zn, while the lower cladding is a 1.0- μm -thick InP layer doped with $3 \times 10^{18} \text{ cm}^{-3}$ of Si. The heterostructure has been fabricated into ridge-guided lasers with 3- μm ridge width and 400- μm cavity length. The facets of the quantum-well and the quantum-dash lasers are all unpassivated. At room temperature, they typically exhibit a threshold current I_{TH} of 22 mA, an emission wavelength of 1600 nm, and a two-facet slope efficiency E_{SLOPE} of 0.35 W/A. More details of the laser can be found in [17].

Both types of quantum-dash lasers were based on heterostructures grown on n -type (100) InP substrates by molecular beam epitaxy. However, different structural designs and growth conditions resulted in different dash sizes and uniformities. The long-dash heterostructure contains five layers of strained InAs dashes, each approximately 300-nm long, 25-nm wide, and 5-nm high. The density of dashes is on the order of 10^{10} cm^{-2} . With five overlapping layers, the dashes cover approximately 75% of the surface area. Each layer of dashes is embedded in a 7.6-nm-thick $\text{In}_{0.64}\text{Ga}_{0.16}\text{Al}_{0.20}\text{As}$ well that is separated by 30-nm-thick $\text{In}_{0.50}\text{Ga}_{0.22}\text{Al}_{0.28}\text{As}$ barriers. In turn, the undoped dash-in-well heterostructure is optically confined in 105-nm-thick $\text{In}_{0.52}\text{Ga}_{0.18}\text{Al}_{0.30}\text{As}$ layers. The long-dash lasers have 4- μm ridge width and 400- μm cavity length. At room temperature, they typically exhibit a threshold current of 44 mA, an emission wavelength of 1565 nm, and a two-facet slope efficiency of 0.17 W/A. More details can be found in [15].

Fig. 1. Threshold current versus ambient temperature of a short-dash laser, a long-dash laser, and a quantum-well laser under pulse biases.

The short-dash heterostructure contains four layers of InAs dashes with an average height of 3 nm and an average width of 18 nm. The length varies significantly from 20 to 75 nm. The dash density is comparable to that of the long-dash heterostructure, but the area coverage is lower. Each short-dash layer is embedded in a 7.6-nm-thick $\text{In}_{0.64}\text{Al}_{0.2}\text{Ga}_{0.16}\text{As}$ well that is separated by 30-nm-thick $\text{In}_{0.50}\text{Ga}_{0.32}\text{Al}_{0.18}\text{As}$ barriers. Optical confinement is provided by 160-nm-thick $\text{In}_{0.52}\text{Ga}_{0.28}\text{Al}_{0.2}\text{As}$ above and below the active layers. The short-dash lasers have 3- μm ridge width and 340- μm cavity length. They typically exhibit a threshold current of 200 mA, an emission wavelength of 1615 nm, and a two-facet slope efficiency of 0.09 W/A. As a result of the wide distribution of the dash sizes, the emission width can be as broad as 76 nm under high injection. More details can be found in [18].

Compared to the quantum-well and long-dash lasers, the short-dash laser has significantly higher threshold current and emission width. This is consistent with slower gain saturation with carrier density in quantum-dot lasers [19]. In addition to higher threshold current, the short-dash laser has stronger temperature dependence (see Fig. 1) and cannot be operated above 40°C . Therefore, the temperature characteristics of all three types of lasers were compared in the same temperature range -50°C to 40°C (see Table I). The relatively high temperature stability of the long-dash laser is expected [2] for highly quantum-confined heterostructures. The relatively low temperature stability of the short-dash laser is unexpected, and may be explained by low dash uniformity and carrier confinement (see Section III). The low dash uniformity of the short-dash laser could also lead to low internal quantum efficiency and low slope efficiency. The temperature dependence of the dynamic properties of all three types of lasers is characterized in detail in the following.

III. INTRINSIC DYNAMICS CHARACTERIZATION

Fig. 2 illustrates the custom setup used to characterize the intrinsic laser dynamics under optical injection modulation. Unlike in electrical injection modulation, in optical injection

Fig. 2. Pulse optical injection modulation setup for intrinsic dynamics characterization.

modulation, the laser under test is electrically biased into lasing, but the modulation is through an optical modulator between the injection laser and the laser under test. This helps reveal the intrinsic dynamics of the laser under test without being hindered by parasitic resistances and capacitances [20] because the series resistance of quantum-dash lasers tends to be higher than that of quantum-well lasers. The present setup uses a 1310-nm narrow-band laser for optical injection. Although the 1310-nm injection can excite carriers in both the dashes and their surrounding wells, due to efficient carrier exchange between the dashes and the wells, the modulation effect of the 1310-nm laser is very similar to that of a 1460–1540-nm tunable laser [21].

The injection laser is coupled to the laser under test via a LiNbO₃ Mach–Zehnder modulator, an optical circulator, and a lensed fiber. The modulated emission of the laser under test is then sensed by a photodiode after using a 1560-nm filter to eliminate the portion of the optical injection reflected by the laser under test. A time-gated two-port RF network analyzer is aided by two RF power amplifiers to modulate the optical modulator between 0.5 and 10 GHz, as well as to detect the output of the photodiode in terms of both magnitude and phase. After standard electrical calibration of the RF network, an optical fiber (see dashed line in Fig. 2) serves as the optical through to calibrate out the RF dispersions of the power amplifiers, the modulator, and the photodiode. All measured modulation responses are normalized by their values at 0.5 GHz to eliminate the uncertainty due to variations in optical coupling efficiency.

Self-heating of the lasers under test is minimized by microsecond pulsing of both the electrical bias and the optical injection, which is a unique capability of the present setup. To this end, a pulse generator is used to bias the laser under test as well as to trigger the network analyzer after suitable delays. Typically, the laser under test is driven by a 5- μ s pulse with a 200-ns rise time and a 5% duty cycle. The RF output of the network analyzer is turned on 0.5 μ s after the laser under test is biased, while the RF input is sampled 2.5 μ s later. All tests are performed in dry air on bare laser dies attached by conductive epoxy to a copper heat

Fig. 3. (a) Measured (symbol) versus modeled (curve) intrinsic response of the quantum-well laser under different bias currents and pulse optical injection modulation. (b) Extracted bias dependence of the relaxation frequency of the quantum-well laser under CW and pulse optical injection modulation.

sink with ± 0.1 °C temperature control. For each type of laser, several devices are measured repeatedly over a course of several months to ensure that the results are representative and reproducible. This setup has been successfully used to characterize quantum-well lasers with highly consistent results [22].

Fig. 3(a) illustrates the measured modulation response of the quantum-well laser under 20 °C and different bias currents above the threshold. It can be seen that the measured response spans a wide dynamic range with low noise, which ensures accurate extraction of dynamic properties. The measured modulation response fits very well [see Fig. 3(a)] the classic frequency dependence of quantum-well lasers [23]

$$M(f) \propto \frac{1}{(f_R^2 - f^2 + j\gamma f/2\pi)} \quad (1)$$

where f_R and γ are the relaxation frequency and the damping factor, respectively. The extracted relaxation frequency confirms that self-heating is indeed minimized in the pulse measurement. Fig. 3(b) compares the bias dependence of f_R^2 extracted from pulse and continuous wave (CW) measurements of a quantum-well laser. It can be seen that while f_R^2 tends to saturate at high currents in the CW measurement, it is linearly dependent on the bias current in the pulse measurement.

Fig. 4. Measured (symbol) versus modeled (curve) modulation response of the three types of lasers under different pulse biases and optical injection modulations at (a) -40°C and (b) 40°C .

Fig. 5. Extracted (symbol) versus linearly fitted (line) relaxation frequency as a function of (a) net injection current and (b) damping factor of the three types of lasers under different ambient temperatures.

IV. TEMPERATURE EFFECTS ON INTRINSIC DYNAMICS

Fig. 4 shows the measured modulation responses under different pulse biases and optical injection modulations at -40°C and 40°C for the three types of lasers. For negligible self-heating, the bias is limited to $300\% I_{\text{TH}}$. This also keeps the resonance peak within the 10-GHz bandwidth of the present test setup. It can be seen that the short-dash laser has stronger temperature dependence than either the quantum-well laser or the long-dash laser. Similar difference is observed at other temperatures, al-

though the data are not shown to limit the length of this paper. In all cases, the frequency dependence can be fitted with (1) to accurately extract the relaxation frequency and the damping factor as a function of temperature. Fig. 5 shows that the extracted f_R^2 is linearly dependent on both the net injection current $I - I_{\text{TH}}$ and the damping factor. The slopes of such linear dependencies can then be used to determine the modulation efficiency E_M and the K factor according to [23] as follows:

$$f_R = E_M \sqrt{I - I_{\text{TH}}} \quad (2)$$

Fig. 6. Measured (symbol) versus fitted (curve) temperature dependence of (a) modulation efficiency and (b) effective differential gain.

and

$$\gamma = K f_R^2 + \frac{1}{\tau_{\text{EFF}}} \quad (3)$$

where τ_{EFF} is the effective carrier lifetime.

Fig. 6(a) plots the extracted E_M as a function of temperature. It can be seen that while the quantum-well laser has the highest modulation efficiency, the long-dash laser is the most stable against temperature. From the modulation efficiency and the slope efficiency, the effective differential gain a' can be calculated according to [24] as follows:

$$a' = \frac{4\pi^2 \alpha_M}{\alpha_M + \alpha_I} \frac{V_{\text{ACT}} h\nu E_M^2}{\Gamma v_G E_{\text{SLOPE}}} \quad (4)$$

where α_M is the mirror loss, α_I is the internal loss, V_{ACT} is the active volume, $h\nu$ is the photon energy, Γ is the optical confinement factor, v_G is the group velocity, and E_{SLOPE} is the slope efficiency. Fig. 6(b) shows the temperature dependence of a' calculated by using the estimated parameter values listed in Table I. It can be seen that in spite of very different heterostructures, a' of the quantum-dash lasers is on the same order as that of the quantum-well laser, in agreement with the theoretical prediction

[9]. In addition, while the long-dash laser is the most stable against temperature, the short-dash laser is the least stable in this temperature range.

The temperature dependence of a' could originate from the temperature dependence of the transport factor χ or the material gain g because [25]

$$a' = \frac{1}{\chi} \frac{dg}{dN} \quad (5)$$

where N is the carrier density in the active region. In a dash-in-well heterostructure, dg/dN could be smaller due to the much higher number of states in the well than in the dash. At elevated temperatures, the majority of the carriers would escape from the dash into the well [8], [26], thereby decreasing dg/dN . This could explain the steeper decrease of a' for the quantum-dash lasers than for the quantum-well laser at elevated temperatures, as well as the generally lower a' for the short-dash laser than for the long-dash laser. Another possible reason for the lower a' of the short-dash laser is its nonuniform size distribution, which would result in a wider carrier distribution and cause some dashes to cease lasing at elevated temperatures [27], [28]. Lastly, the deteriorated carrier confinement in the short-dash, as indicated by its high threshold current at elevated temperatures (see Fig. 1), would also suppress a' .

The effective differential gain in conjunction with the K factor can be used to extract the gain compression factor ε according to [23] as follows:

$$K = 4\pi^2 \left(\tau_p + \frac{\varepsilon}{v_G a'} \right) \quad (6)$$

where τ_p is the photon lifetime estimated from the cavity length, as listed in Table I. Fig. 7 shows the temperature dependence of the extracted K factor, the gain compression factor, and the effective carrier lifetime. It can be seen in Fig. 7(a) that for the quantum-well laser, the K factor slightly increases with increasing temperature. Combined with the slight decrease of its effective differential gain [see Fig. 6(b)], it results in a nearly temperature-independent gain compression factor ε , as shown in Fig. 7(b). Similarly, the long-dash laser has nearly temperature-independent K factor, effective differential gain, and gain compression factor, as expected. In comparison, the short-dash laser exhibits strong temperature dependence in its K factor, effective differential gain, and gain compression factor.

Fig. 7(b) shows that for both the long-dash and short-dash lasers, the gain compression factor is approximately twice that of the quantum-well laser, which appears to be the main reason the quantum-dash lasers have narrower modulation bandwidth than the quantum-well laser. The study on semiconductor optical amplifiers has attributed [19] the difference in the gain compression factor to the difference in carrier-heating mechanisms. Specifically, carrier heating is dominated by free-carrier absorption in quantum dashes, but by stimulated transition in quantum wells. This can also explain the stronger temperature dependence of the gain compression factor of the short-dash laser because its much higher threshold current and higher carrier density would lead to stronger carrier heating by free-carrier absorption. Lastly, carrier heating by free-carrier absorption could be stronger in the

Fig. 7. Extracted (symbol) and fitted (curve) temperature dependence of (a) K factor, (b) gain compression factor, and (c) effective carrier lifetime.

quantum dashes simply due to the difference in the properties of InAlGaAs and InGaAsP.

It can be seen from Fig. 7(c) that while the effective carrier lifetimes of the all three lasers decrease with increasing temperature, the effective carrier lifetimes of both quantum-dash lasers are approximately half of that of the quantum-well laser.

This implies that Auger recombination [29] dominates carrier recombination in all three lasers, while defect-related recombination [30] introduces additional temperature dependence in the short-dash laser due to its larger surface-to-volume ratio.

V. CONCLUSION

Compared to quantum-well lasers, the present quantum-dash lasers have comparable effective differential gain but approximately twice the gain compression factor, probably due to carrier heating by free-carrier absorption as opposed to stimulated transition. Therefore, the narrower modulation bandwidth of the quantum-dash lasers appears to be mainly limited by the gain compression factor.

As expected, the long-dash laser exhibits higher temperature stability than the quantum-well laser. However, the short-dash laser exhibits lower temperature stability, probably due to its higher surface-to-volume ratio and nonuniform dash sizes. Since short and nonuniform dashes are required for its broadband emission [5], careful tradeoff must be considered between its emission and modulation characteristics.

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