Gain compression coefficient and above-threshold linewidth enhancement factor in InAs/GaAs quantum dot DFB lasers

H. Su[*a], L. Zhang[b], A. L. Gray[b], R. Wang[b], P. M. Varangis[b] and L. F. Lester[a]
[a]Center for High Technology Materials, University of New Mexico, 1313 Goddard SE, Albuquerque, NM 87106
[b]Zia Laser, Inc., Albuquerque, NM 87106

ABSTRACT

We measure, for the first time, the gain compression coefficient and above-threshold linewidth enhancement factor (alpha parameter) in quantum dot (QD) distributed feedback lasers (DFB) by time-resolved-chirp (TRC) characterization. The alpha parameter is measured to be 2.6 at threshold and increases to 8 when the output power of the QD DFB is increased to 3 mW. The dependence of the above-threshold alpha parameter on the optical power is found to be stronger than the optical gain compression effect alone can predict. The inhomogeneous gain broadening, gain saturation at the ground states and carrier filling in the excited states in QDs are proposed to explain the results.

1. INTRODUCTION

It is very natural for quantum dots (QD) to become attractive after the success of quantum well (QW) hetero-structures. The development of quantum well devices confirms the functionality of the quantum confinement of carriers in semiconductors and fosters the concepts and tools which are essential to design, fabricate and characterize QD devices. Theoretically, QD lasers represent the ultimate case of the application of the size quantization concept to semiconductor hetero-structure lasers [1]. The advantages of quantum dots compared to quantum wells stem from their unique delta-function-like density of states resulting from the 3-dimensional confinement of carriers. Consequently the energy levels of QDs are less convolved with each other compared to those of QWs. After the creation of QD lasers in 1993 and early 1994 [2, 3], various advantages of QDs have been verified in actual devices, including the low transparency current [4], increased material and differential gain [5], less temperature sensitivity [6] and reduced linewidth enhancement factor (α parameter) [7]. Furthermore, QDs can extend the achievable wavelengths on given substrates since the three dimensional structure of the nanometer-scale dots helps to relax the strain from the lattice mismatch while minimizing dislocation formation. One of the real applications of this is the growth of 1.3 μm InAs QD lasers on GaAs substrates which are much cheaper and easier to handle compared to InP. Finally, as QDs are spatially separated and the carriers are localized once they get captured into the dots, QD gain media are more resistant to defects than QW structures [8, 9].

Among the various properties of QD lasers, the linewidth enhancement factor is one of the most important. It is related to the frequency purity and stability of the laser including such characteristics as the static linewidth [10], external feedback sensitivity [11] and chirp. Different groups report various values of the linewidth enhancement factor in QD samples. Typically the linewidth enhancement factor is measured using the Hakki-Paoli technique which requires a delicate control of the temperature of testing. The published results range from negative to about 2 [12, 13]. A value of 0.1 is reported by T. Newell, et. al. [7] in single-stack QD lasers and a minimum of about 1.0 is measured by A. Ukhanov, et. al. [14] in a multi-stack sample. It is found that the excited states in the dots and the continuum states in the QWs have severe effects on the alpha factor of the ground state [15]. In tunneling-injection QD devices, alpha is measured to 0.15 [16] and 0.7 [17,18]. As one of its drawbacks, the Hakki-Paoli method is applicable only under threshold and in Fabry-Perot (FP) lasers. There is still no systematic study of the alpha factor in a real QD laser operating above threshold. Unlike the case of QW lasers, the carrier density in QD lasers is not well-clamped at threshold due to the inhomogeneous gain broadening in QDs. Therefore, the above-threshold alpha could behave differently from the below-threshold one. In this work, we measure the gain compression coefficient and above-

[*] huisu@chtm.unm.edu; Tel. (505) 272-7868, Fax. (505) 272-7801

Physics and Simulation of Optoelectronic Devices XIII, edited by Marek Osinski, Fritz Henneberger, Hiroshi Amano, Proc. of SPIE Vol. 5722 (SPIE, Bellingham, WA, 2005)
0277-786X/05/$15 · doi: 10.1117/12.591105

threshold linewidth enhancement factor through chirp characterization of single-mode QD distributed feedback lasers (DFB). We demonstrate that the alpha is strongly dependent on the output power and propose an explanation for that based on the carrier dynamics in QDs.

2. DEVICE STRUCTURE AND EXPERIMENTAL SETUP

The QD DFBs are fabricated with self-assembled InAs nano-dots grown on a GaAs substrate. After the ridge waveguide is defined by etching, an absorptive chromium layer is deposited laterally to the waveguide to form a periodic modulation on the loss of the lasing mode and thus the mode selection mechanism is introduced. The details of the material growth and processing of the QD devices are given in ref. [19, 20]. The chirp performance of the devices is characterized by time-resolved-chirp (TRC): a digital 2.5 Gbps modulation with a peak-to-peak voltage of 250 mV is applied to the DFB laser, and the corresponding wavelength shift of the laser is measured using the optical filter in an Agilent 16401B optical spectrum analyzer. The algorithm and detailed setup of the TRC measurement is given in ref. [21]. As shown in Fig. 1, the threshold of the device is 5 mA and the slope efficiency is approximately 0.1 mW/mA. The resistance of the device is calculated to be 20.6 Ohms in the DC-bias range of 10 mA – 40 mA. The device has a side mode suppression ratio of about 50 dB with a DFB wavelength of 1320 nm. All the testing is done with the heat sink temperature controlled to be 20 ^{o}C. Two 30-dB isolators are cascaded to avoid unintended external optical feedback into the QD DFBs.

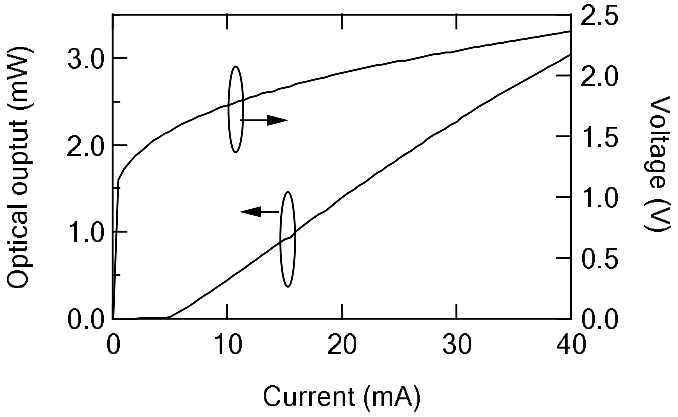

Fig. 1. LIV curves of the QD DFB for the TRC measurement.

3. RESULTS AND DISCUSSION

Chirp of a semiconductor laser is defined as the frequency shift of the lasing wavelength under external modulation. Based on the rate-equation model [22] considering the coupling between the gain and index in the active medium, the relationship between the power, P, and the frequency chirp, $\Delta\nu$, can be derived from the following two equations:

$$\frac{dP}{dt} = (\frac{\Gamma v_g g}{1+\varepsilon_P P} - G_{th})P + R_{sp} \quad (1)$$

$$\Delta\upsilon = \upsilon - \upsilon_{th} = -\frac{\upsilon_{th}}{n}\Delta n = -\frac{\upsilon_{th}}{n}\frac{\partial n}{\partial g}(g - g_{th}) = \frac{\alpha}{4\pi}\Gamma v_g (g - g_{th}) = \frac{\alpha}{4\pi}(\Gamma v_g g - G_{th}) \quad (2)$$

Consequently, the frequency chirp can be expressed as:

$$\Delta\upsilon \approx \frac{\alpha}{4\pi}[(1+\varepsilon_P P)\frac{dP}{Pdt} + \varepsilon_P P G_{th}]$$

$$= \frac{\alpha(1+\varepsilon_P P)}{4\pi}[\frac{dP}{Pdt} + \frac{\varepsilon_P P G_{th}}{(1+\varepsilon_P P)}]$$

$$= \frac{\alpha_{eff}}{4\pi}\left[\frac{dP}{Pdt} + \frac{\varepsilon_P P G_{th}}{1+\varepsilon_P P}\right] \quad (3)$$

where α_{eff} is the effective linewidth enhancement factor, P is the optical power, t is time, ε_P is the gain compression coefficient associated with the optical power, g is the material gain, v_g is the group velocity, Γ is the optical confinement factor, and G_{th} is the threshold gain of the laser. In a homogeneously broadened gain medium, the carrier density and distribution are clamped at threshold, and the change of the effective linewidth enhancement factor is due to the decrease of the differential gain from gain compression. Therefore, the effective alpha can be formulated as:

$$\alpha_{eff} = \alpha_0(1+\varepsilon_p P) \quad (4)$$

where α_0 is the linewidth enhancement factor at threshold [22]. Since the carrier distribution is clamped, α_0 itself does not change as the output power increases. However, since inhomogeneous gain broadening is severe in QD gain media, the carrier density and distribution in QD lasers are not clamped at threshold. This phenomenon is substantiated by the fact that the laser can switch to excited-state lasing from ground-state lasing as the current injection increases, indicating a carrier accumulation in the excited states even though the ground-state is lasing. The filling of the excited states inevitably increases the alpha factor of the ground-state [14, 23], introducing additional dependence of the alpha parameter on the output power. Therefore, we use the parameter ε_α, rather than ε_P, to describe this dependence and Eqn. (3) needs to be modified into:

$$\alpha_{eff} = \alpha_0(1+\varepsilon_\alpha P) \quad (5)$$

where ε_α is the parameter characterizing the power dependence of the above-threshold linewidth enhancement factor, including the normal gain compression, gain saturation with carrier density and excited-state filling effects in QDs.

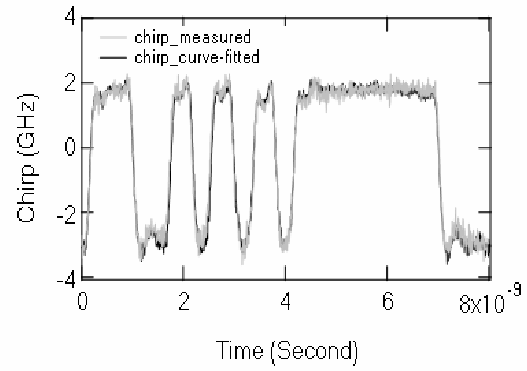

Fig. 1 The measured and curve-fitted chirp of the QD DFB under 25 mA DC bias with a peak-to-peak modulation voltage fixed to be 250mV.

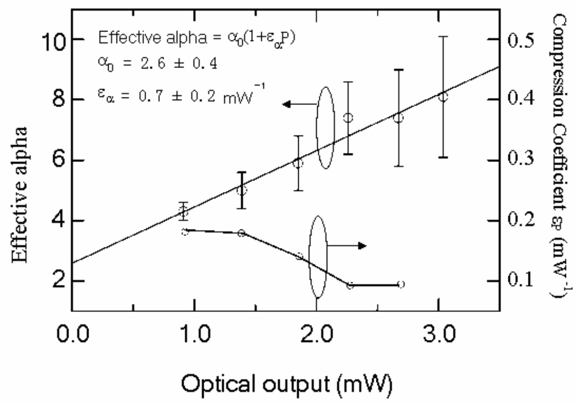

Fig. 2 The effective alpha α_{eff} and gain compression coefficient ε_P at the different output power of the QD DFB.

Fig. 1 gives the measured chirp with a DC bias of 25 mA and its curve-fit based on Eqns. (3) and (5). In Fig. 2, the effective alpha α_{eff} and ε_P from the curve-fitting are plotted versus different output optical power. The alpha factor at threshold is found to be 2.6 ± 0.4 and ε_α 0.7 ± 0.2 mW^{-1} by curve-fitting the measured effective alpha as a linear function of the output power. The value of alpha at threshold is consistent with the result given in ref. [14] that uses the Hakki-Paoli technique. On the other hand, the gain compression coefficient ε_p is curve-fitted to be 0.2 ± 0.1 mW^{-1}, corresponding to 1.6-3.2 x 10^{-16} cm^{-3} in terms of the internal-cavity photon density given the DFB cavity parameters [10]. This ε_p is one order of magnitude higher than the typical value of 10^{-17} cm^{-3} of QWs. It is notable that ε_p is three times smaller than ε_α. As discussed above, this discrepancy between ε_α and ε_p can be explained in part by the carrier accumulation in the excited states in QDs as the current injection increases [23]. The other possible source of the disparity–gain saturation with carrier density–is treated analytically next.

The Effect of Gain Saturation on the Alpha Parameter

The abrupt gain saturation observed in quantum dot gain media is well known. For a steady state condition well above the threshold, the pure gain at the lasing wavelength must equal the threshold loss. Therefore, the uncompressed material gain will increase with the output power as the following equation:

$$g = g_{th}(1+\varepsilon_P P) \quad (6)$$

with g_{th} being the threshold material gain. For simplicity, the following equation is used to describe the hard gain saturation of QD media,

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

where the g_{max} is the maximum gain for the ground-state lasing, N is the carrier density, N_{tr} the transparency carrier density, and the factor of *ln2* is used to equalize the maximum gain and maximum loss in QD gain media. Fig. 3 plots the gain versus carrier density normalized to the transparency carrier density in QDs. In the following analysis, the degree of carrier density related gain saturation is expressed as the decrease of the different gain. When the laser is above threshold, Eqn. (6) and (7) yield an expression for the differential gain, a, at the ground state:

$$a \equiv \frac{dg}{dN} = \frac{\ln 2}{N_{tr}}(g_{\max} - g) = \frac{\ln 2}{N_{tr}}(g_{\max} - (1+\varepsilon_P P)g_{th}) = a_0(1 - \frac{g_{th}}{g_{\max} - g_{th}}\varepsilon_P P) \quad (8)$$

where the a_0 is the differential gain at threshold. The decrease of the differential gain given by Eqn. (8) is directly related to the response of the QD device under direct ac modulation [24]. Measuring the frequency response as function of power is a common method for detecting gain compression in semiconductor lasers. In the case of QDs undergoing strong gain saturation with carrier density, the resonance frequency is given as:

$$\omega_R^2 = \frac{v_g g_{th} aP}{1+\varepsilon_p P} \approx \frac{v_g g_{th} a_0 P}{1 + \frac{g_{\max}}{g_{\max} - g_{th}}\varepsilon_P P} \quad (9)$$

Eqn. (9) indicates that the gain compression effect on the modulation bandwidth of a QD laser is enhanced with an effective gain compression coefficient due to the gain saturation of

$$\varepsilon_{eff} = \frac{g_{\max}}{g_{\max} - g_{th}}\varepsilon_P \quad (10)$$

For typical QD DFBs discussed in this work, g_{max} and g_{th} are about 15 cm^{-1} and 12 cm^{-1}, respectively. The gain compression effect is enhanced by a factor 5 in these devices, and a severe limitation on the modulation bandwidth has been previously observed and partly explained by this gain saturation with carrier density [25]. In the following analysis, we incorporate the consequences of Eqn. (8) on the differential gain with the effect of the excited states on the ground states and derive a novel expression for the alpha parameter.

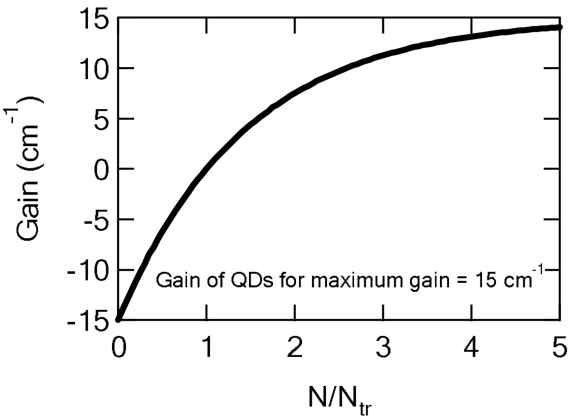

Fig. 3 The gain vs. normalized carrier density in QD gain media. The maximum ground-state gain is set to 15 cm^{-1}, which is typical in the devices studied in this paper.

As represented in Fig. 4, although the net gain at the ground state is clamped at threshold, the carrier density at the excited states keeps growing due to spectral hole burning. Experimentally, lasing at the excited states is observed in the QD devices under high injection. Therefore, Eqn (4) is not strictly applicable to the gain compression effect in QDs. To model the effective alpha parameter in QDs, we simply divide the energy levels into ground states and excited states. The gain compression occurs locally within the homogeneous broadening of the ground states. Therefore, the index change at the ground-state wavelength can be caused by both of the gain variation at the ground states and excited states in QDs.

$$\delta n = \alpha_e \delta g_e + \alpha_g \delta g_g = (\alpha_e \frac{a_e}{a_g} + \alpha_g)\delta g_g \equiv \alpha \delta g \qquad (11)$$

where δn and δg_g are the changes of the gain and refractive index at the ground state, respectively, α is the alpha parameter actually measured in the device, a_e and a_g are the differential gains at the excited and ground states respectively, α_e describes the change of the ground-state index caused by the excited state gain, and α_g describes the ground-state index change caused by the ground-state gain variation. When the laser is above threshold, α_g will increase as $\alpha_g(1+\varepsilon_P P)$, similar to the case of QWs, since it is from the energy levels within the homogeneous broadening. By putting Eqn. (4) and (8) into Eqn. (11), we have the dependence of the alpha parameter on the optical power as

$$\alpha(P) = \alpha_e \frac{a_e}{a_0 (1 - \frac{g_{th}}{g_{\max} - g_{th}} \varepsilon_P P)} + \alpha_g (1 + \varepsilon_P P) \qquad (12)$$

where the first term on the right side is the contribution from the carrier filling in the excited states that is related to the gain saturation in the ground state, and the second term is the gain compression effect at the ground state. In the case of strong gain saturation or $\alpha_g=0$ when the DFB mode is close to the ground-state gain peak, Eqn. (12) can be further simplified to:

$$\alpha(P) = \frac{\alpha_0}{(1 - \frac{g_{th}}{g_{\max} - g_{th}} \varepsilon_P P)} \qquad (13)$$

indicating the dependence of the alpha parameter on the optical power is enhanced by a factor of $g_{th}/(g_{max}-g_{th})$, that is a factor of 4 for the case in which g_{max} and g_{th} are about 15 cm^{-1} and 12 cm^{-1}, respectively. Therefore, a larger maximum gain is also essential for a lower alpha parameter in QD gain media.

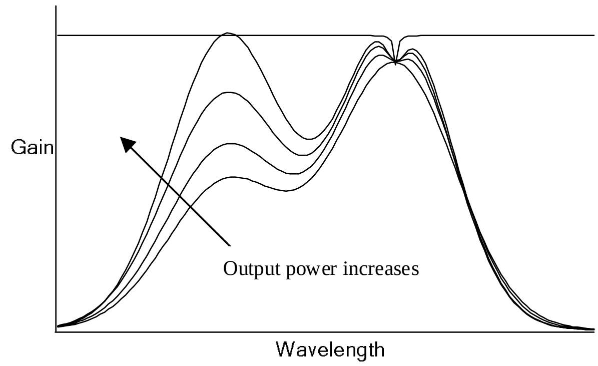

Fig. 4 The distortion of the gain spectrum of QD gain media due to the inhomogeneous broadening and spectral hole burning effects in the QD DFB.

4. CONCLUSION

In this paper, time resolved chirp is characterized in a QD DFB for the first time and the gain compression coefficient in the QD DFB is measured to be 0.2±0.1 mW^{-1}, corresponding to 1.6-3.2 x 10^{-16} cm^{-3} in terms of the internal-cavity photon density. The linewidth enhancement factor is measured to be α_0=2.6±0.5 at threshold and ε_α= 0.7±0.2 mW^{-1} in the devices. The dependence of the linewidth enhancement factor on the output power is stronger than the pure gain compression effects can predict. The discrepancy between ε_α and ε_P can be explained by the inhomogeneous gain broadening, gain saturation with carrier density, and the carrier accumulation in the excited states of the QDs.

REFERENCES

1. Y. Arakawa and H. Sakaki, "Multidimensional Quantum Well laser and Temperature-Dependence of its Threshold Current," *Applied Physics Letters* **40**, 939-941.
2. N. Kirstaedter, N. N. Ledentsov, M. Grundmann, D. Bimberg, V. M. Ustinov, S. S. Ruvimov, M. V. Maximov, P. S. Kopev, Z. I. Alferov, U. Richter, P. Werner, U. Gosele, and J. Heydenreich, "Low-Threshold, Large T-0 Injection-Laser Emission From (InGa)As Quantum Dots," *Electronics Letters* **30**, 1416-1417.
3. N. N. Ledentsov, V. M. Ustinov, A. Y. Egorov, A. E. Zhukov, M. V. Maksimov, I. G. Tabatadze, and P. S. Kopev, "Optical-Properties of Heterostructures with InGaAs-GaAs Quantum Clusters," *Semiconductors* **28**, 832-834 (1994).
4. G. T. Liu, A. Stintz, H. Li, K. J. Malloy, and L. F. Lester, "Extremely low room-temperature threshold current density diode lasers using InAs dots in In0.15Ga0.85As quantum well," *Electronics Letters* **35**, 1163-1165 (1999).
5. M. Asada, Y. Miyamoto, and Y. Suematsu, "Gain and the Threshold of 3-Dimensional Quantum-Box Lasers," *IEEE Journal of Quantum Electronics* **22**, 1915-1921 (1986).
6. O. B. Shchekin and D. G. Deppe, "1.3 mu m InAs quantum dot laser with T-o=161 K from 0 to 80 degrees C," *Applied Physics Letters* **80**, 3277-3279 (2002).
7. T. C. Newell, D. J. Bossert, A. Stintz, B. Fuchs, K. J. Malloy, and L. F. Lester, "Gain and linewidth enhancement factor in InAs quantum-dot laser diodes," *IEEE Photonics Technology Letters* **11**, 1527-1529 (1999).

8. N. A. Sobolev, A. Cavaco, M. C. Carmo, M. Grundmann, F. Heinrichsdorff, and D. Bimberg, "Enhanced radiation hardness of InAs/GaAs quantum dot structures," *Physica Status Solidi B-Basic Research* **224**, 93-96 (2001).
9. F. Guffarth, R. Heitz, M. Geller, C. Kapteyn, H. Born, R. Sellin, A. Hoffmann, D. Bimberg, N. A. Sobolev, and M. C. Carmo, "Radiation hardness of InGaAs/GaAs quantum dots," *Applied Physics Letters* **82**, 1941-1943 (2003).
10. H. Su, L. Zhang, R. Wang, T. C. Newell, A. L. Gray, and L. F. Lester, "Linewidth study of InAs-InGaAs quantum dot distributed feedback lasers," *IEEE Photonics Technology Letters* **16**, 2206-2208 (2004).
11. H. Su, L. Zhang, A. L. Gray, R. Wang, T. C. Newell, K. J. Malloy, and L. F. Lester, "High external feedback resistance of laterally loss-coupled distributed feedback quantum dot semiconductor lasers," *IEEE Photonics Technology Letters* **15**, 1504-1506.
12. P. M. Smowton, E. J. Pearce, H. C. Schneider, W. W. Chow, and M. Hopkinson, "Filamentation and linewidth enhancement factor in InGaAs quantum dot lasers," *Applied Physics Letters* **81**, 3251-3253 (2003).
13. A. V. Uskov, E. P. O'Reilly, D. McPeake, N. N. Ledentsov, D. Bimberg, and G. Huyet, "Carrier-induced refractive index in quantum dot structures due to transitions from discrete quantum dot levels to continuum states," *Applied Physics Letters* **84**, 272-274 (2004).
14. A. A. Ukhanov, "Study of the Carrier-induced optical properties in III-V quantum confined laser nano-structures," PhD dissertation, the University of New Mexico, 2004.
15. A. V. Uskov, E. P. O'Reilly, D. McPeake, N. N. Ledentsov, D. Bimberg, and G. Huyet, "Carrier-induced refractive index in quantum dot structures due to transitions from discrete quantum dot levels to continuum states," *Applied Physics Letters* **84**, 272-274 (2004).
16. P. K. Kondratko, S. L. Chuang, G. Walter, T. Chung, and N. Holonyak, "Observations of near-zero linewidth enhancement factor in a quantum-well coupled quantum-dot laser," *Applied Physics Letters* **83**, 4818-4820 (2003).
17. S. Fathpour, P. Bhattacharya, S. Pradhan, and S. Ghosh, "Linewidth enhancement factor and near-field pattern in tunnel injection In0.4Ga0.6As self-assembled quantum dot lasers," *Electronics Letters* **39**, 1443-1445 (2003).
18. K. Kamath, J. Phillips, H. Jiang, J. Singh, and P. Bhattacharya, "Small-signal modulation and differential gain of single-mode self-organized In0.4Ga0.6As/GaAs quantum dot lasers," *Applied Physics Letters* **70**, 2952-2953 (1997).
19. R. Krebs, F. Klopf, S. Rennon, J. P. Reithmaier, and A. FORCHEL, "High frequency characteristics of InAs/GaInAs quantum dot distributed feedback lasers emitting at 1.3 mu m," *Electronics Letters* **37**, 1223-1225 (2001).
20. L.Zhang, R.Wang, Z.Zou, T.Newell, D.Webb, P.Varangis, and L.Lester. InAs quantum dot DFB lasers on GaAs for uncooled 1310nm fiber communications. *Optical Fiber Communication Conference,* Atlanta, GA. 2003.
21. Agilent Technologies. Making Time-Resolved Chirp Measurements using the optical spectrum analyzer and digital communication analyzer. 2004. Application Note 1550-7.
22. K.Petermann, *Laser diode modulation and noise*, Kluwer Academic Publishers, 1991.
23. A. Markus, J. X. X. Chen, O. Gauthier-Lafaye, J. G. Provost, C. Paranthoen, and A. Fiore, "Impact of intraband relaxation on the performance of a quantum-dot laser," *IEEE Journal of Selected Topics in Quantum Electronics* **9**, 1308-1314 (2003).
24. L.A.Coldren and S.W.Corzine, *Diode lasers and Photonics Integrated Circuits,* John Wiley & Sons, INC., 1995, 213-221.
25. H. Su, "Gain compression effects in QD DFB lasers," 2004 IEEE Semiconductor Laser Workshop, San Francisco, California, May 2004.