Anticompetition Between Laser Modes in Quantum-Dot Laser

Yi-Shin Su, Ding-I Chiang, and Ching-Fuh Lin

Abstract—**Anticompetition behavior is observed in a InAs quantum-dot (QD) laser with external wavelength control. Unlike the competition behavior observed in other QD lasers, in this experiment, the laser emission induced by external feedback at the ground state wavelength improves the excited-state emission at 1170 nm by 13 dB. Such an anticompetition phenomenon is most obvious as the feedback wavelength differs from 1250 nm, the original lasing wavelength, by 15 nm. This anticompetition behavior is explained by the sharing of QDs between the laser emission induced by the feedback and the original laser oscillation.**

Index Terms—**Carrier dynamics, nonlinear optical device, quantum dots (QDs), semiconductor lasers.**

I. INTRODUCTION

QUANTUM-DOT (QD) lasers are attractive because they exhibit excellent properties such as extremely low operation current density, high thermal stability, and so on [1]–[4]. Although high-quality QDs can be grown by the Stranski–Krastanov method, there is inevitable variation in the dot sizes and thus the quantized energy levels. The inhomogeneous broadening of the gain spectrum due to variation in the dot size provides complex dynamical behaviors to be explored. In all-optical networks, the application or the elimination of the gain competition phenomenon is of special importance. Using QDs as the gain media, optical amplifiers can achieve broad bandwidth and low crosstalks [5]–[8]. This property is also preferred when amplification of mode-locked pulses with broad spectrum is considered [9]. On the other hand, QD devices still exhibit strong localized spectral hole burning due to homogeneous broadening of each QD [7]. This special combination of weak global competition and strong local competition is suitable for single-device all-optical multichannel switches [10], [11]. In addition to the competition behaviors, QD lasers can have anticompetition behaviors by the mechanism of optical pumping [12]. In this work, we found another mechanism that leads to anticompetition behavior. With this new mechanism, the laser emission at the ground state induced by grating feedback enhances the emission of the excited states. This behavior is different from the competition behavior normally observed in QD amplifiers, and is also different from the anticompetition previously observed in the QD two-wavelength laser [12].

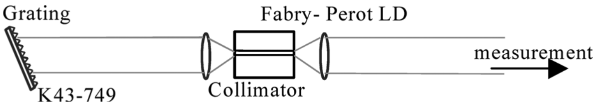

Fig. 1. External cavity laser setup.

II. EXPERIMENETAL SETUP AND QD LASER CHARACTERISTICS

This anticompetition behavior is observed in a QD laser under the experimental setup shown in Fig. 1. This laser chip has InAs QDs as the gain material. The QDs are embedded in the InGaAs–GaAs quantum well. The substrate is GaAs. Two types of QD layers with different size distributions are used together to enhance the effect of inhomogeneous broadening. One type of QD layer has the center emission wavelength at 1.24 μm. The other has the center emission wavelength at 1.28 μm. The fabricated laser chip has 497-μm cavity length and 4-μm waveguide width. Without using the external cavity, this Fabry–Pérot laser diode has the threshold current of 18.1 mA. The ground-state laser emission covers many Fabry–Pérot modes with a peak wavelength at 1250 nm. The amplified spontaneous emission of the excited states is observed to be between 1170 and 1180 nm.

In the setup, the light emitted from both facets is collimated using two collimators. At one side of the laser diode, a grating is used to provide control on the emission wavelength of the external-cavity laser. The emission wavelength controlled by the grating is called the feedback wavelength for the purpose of description simplicity later. In the tunable range of this laser, the reflection efficiency of this grating is above 60%. The emission from the other side is used for spectral analysis.

III. ANTICOMPETITION BEHAVIOR

In the grating-controlled external-cavity laser, it is well known that the lasing characteristics are influenced by the feedback wavelength. Here we further discover that the laser emission at the ground-state wavelength induced by the external feedback does not necessarily compete with the emission at the excited-state wavelength, such as the case when the feedback wavelength is at 1265 nm. Fig. 2(a) shows the emission spectrum of this device at 64 mA without the external cavity, while Fig. 2(b) is the emission spectrum with the feedback wavelength at 1265 nm. When the grating feedback is applied

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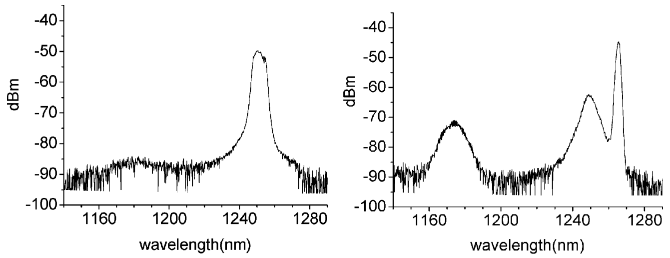

(a) (b)

Fig. 2. Emission spectra of this laser at 64 mA: (a) no external feedback; (b) external feedback at 1265 nm.

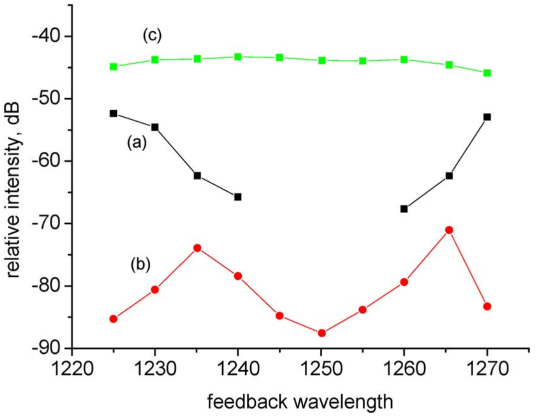

Fig. 3. Amplitude of each peak in the emission spectra at 64 mA. (a) Original laser emission at 1250 nm. (b) Excited-state emission at 1170 nm. (c) Laser emission at feedback wavelength. Without feedback, the peak intensity of the original laser emission at 1250 nm is −49.72 dB, and the peak excited-state emission intensity is −84.08 dB.

at 1265 nm, the external cavity induces a new laser emission at this feedback wavelength. At the same time, the peak intensity at the original laser emission, 1250 nm, drops by 12.6 dB, but the emission spectrum corresponding to the excited states increases significantly by 13 dB. The spectral changes are clearly observed by comparing Figs. 2(a) and (b). Therefore, the increase of laser intensity at 1265 nm results in the increase of emission intensity from the excited states, the anticompetition phenomenon.

This anticompetition phenomenon is dependent on the feedback wavelength. The peak intensity of the original ground-state laser emission and the excited-state emission are plotted against the feedback wavelength as curves (a) and (b), respectively, in Fig. 3. The intensity of the laser emission at the feedback wavelength is also shown in Fig. 3 [curve (c)]. The injection current for the measurements shown in Fig. 3 is 64 mA. In Fig. 3, the laser emission intensity at the feedback wavelength, curve (c), only varies slightly, less than 3 dB in the tuning range, while the emission intensity of excited states, curve (b), varies for more than 16 dB. The excited-state emission intensity has maximum when the feedback wavelength is at 1235 and 1265 nm, which are both 15 nm away from the original laser emission of the ground states. In both cases, the peak emission intensity of the excited states is 13 dB higher than the value without feedback. When the feedback wavelength moves further away from 1250 nm, the peak intensity of the excited-state emission decreases and the intensity of the original laser emission at 1250 nm recovers. The effect of external feedback on the emission property is reduced. On the other hand, when the feedback wavelength shifts from 1235 or 1265 nm toward 1250 nm, the peak intensity of the excited-state emission decreases and finally drops to lower than the value without feedback. The original laser emission at 1250 nm decreases, too. For the feedback wavelength at 1250 nm, the external feedback is observed to compete with the original emissions of both the excited states and the ground states.

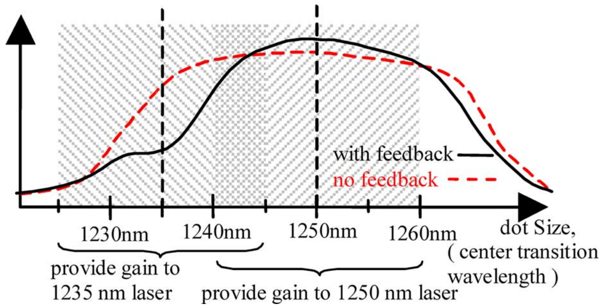

Fig. 4. Carrier distribution of the ground states under the influence of external feedback. Solid line is the case when feedback is applied at 1235 nm. Dashed line is the case without external feedback.

IV. DISCUSSION

This peculiar behavior can be explained by the interaction between QDs of different transition wavelengths. The gain spectrum of each single QD has a finite linewidth. This linewidth measured by the gain competition effect ranges from 12 to 24 nm [7], [11]. For simplicity of discussion, let us assume the homogeneous-broadened gain spectrum of each QD covers a 20-nm spectral range. By this assumption, the laser emission at 1250-nm wavelength is contributed by QDs with transition wavelength between 1240 and 1260 nm. Considering the case with another laser emission at 1235 nm induced by grating feedback, the gain at 1235 nm is contributed by QDs with transition wavelength from 1225 to 1245 nm. The QDs with a transition wavelength between 1240 and 1245 nm provide gain to both emissions at 1235 and 1250 nm, while the QDs with a transition wavelength between 1245 and 1260 nm provide gain to the emission at 1250 nm only. As illustrated in Fig. 4, the carrier population in QDs with a transition wavelength from 1240 to 1245 nm decreases due to the stimulated emission induced by the 1235-nm laser emission. Because these QDs also provide gain to the original laser emission at 1250 nm, the 1250-nm laser intensity decreases.

In QDs with a transition wavelength longer than 1260 nm, the carriers do not provide gain for laser emission at 1235 nm, but the carrier population should also decrease by a small amount due to interdot carrier redistribution. However, the situation is different for QDs with transition wavelengths from 1245 to 1260 nm. The 1250-nm laser induces significant stimulated recombination in these QDs. The stimulated recombination rate is proportional to the product of the laser intensity at 1250 nm and the provided gain. When the laser intensity at 1250 nm decreases, the stimulated recombination rate in these

QDs decreases. Thus, in the QDs, which contribute gain to 1250 nm only, extra carriers accumulate in the ground states and the number of empty ground states decreases, as illustrated in Fig. 4. Because of the Pauli exclusion principle, excited-state carriers can only fall to empty sites of the ground states. Thus, the rate of excited-state carriers falling to the ground states decreases. The excited-state carriers in these QDs also increase and additional emissions can be observed at the corresponding wavelength, 1170 nm. This is the observed anticompetition effect in this experiment.

The above model also explains the reduction of this anticompetition effect when the feedback wavelength moves toward or away from 1235 or 1265 nm. As the separation between the feedback wavelength and 1250 nm increases, the amount of QDs shared by both wavelengths decrease. Thus, less QDs contributing gain at 1250 nm are affected by the external feedback. The laser emission at 1250 nm recovers and the carrier population of the 1250-nm QDs decreases again.

From the above arguments, moving the feedback wavelength closer to 1250 nm is expected to increase the anticompetition effect. However, the emission intensity of the excited states decreases when the feedback wavelength moves to less than 10 from 1250 nm. The reason is as follows. When the feedback wavelength lies within the homogeneously broadened gain spectrum of the QDs with 1250-nm transition wavelength, the laser emission at the feedback wavelength can also induce stimulated recombination in these 1250-nm QDs. This results in strong carrier competition. Ground-state carriers in these 1250-nm QDs will decrease due to the stimulated recombination induced by the laser emission at the feedback wavelength. The anticompetition effect is balanced by the usual competition effect.

Although we assume the homogeneously broadened gain spectrum to cover 20-nm spectral rang, a smaller value of homogeneous-broadening linewidth can also explain the experiment well. The reason is because the competition effect due to the homogeneous broadening is not limited to the full-width at half-maximum (FWHM) range. When the feedback wavelength is close to 1250 nm, the competition effect is strong. It gradually decreases as the feedback wavelength moves away from 1250 nm. In the experiment, the competition effect is more significant than the anticompetition effect when the feedback wavelength is less than $+/-10$ from 1250 nm. If this $+/-10$-nm wavelength span corresponds to the 90% width of the homogeneously broadened gain spectrum, then the homogeneous-broadening linewidth should have 9-meV FWHM. Whether this $+/-10$-nm wavelength span is the 50% width (16-meV homogeneous broadening) or the 90% width (9-meV homogeneous broadening) depends on the relative strengths of the two counteracting effects, the competition and the anticompetition.

V. CONCLUSION

A new type of anticompetition behavior was observed in the QD external-cavity tunable laser. In this investigation, we discovered that the laser emission at the ground state induced by grating feedback enhances the emission of the excited states. This anticompetition phenomenon is dependent on the feedback wavelength. The increment in the excited-state emission intensity is maximum when the feedback wavelength is at 1235 and 1265 nm, which are both 15 nm away from the original laser emission, 1250 nm. The anticompetition behavior is explained by the sharing of QDs between the laser emission induced by the feedback and the original laser oscillation. When the feedback wavelength moves away from 1250 nm, the number of shared QDs decreases, leading to the reduced anticompetition. On the other hand, when the feedback wavelength moves toward 1250 nm, the competition between the laser emission induced by the feedback and the original laser oscillation increases as a result of homogeneous broadening. It also leads to the apparent reduction in the anticompetition.

REFERENCES

[1] N. Kirstaedter, N. N. Ledentsov, M. Grundmann, D. Bimberg, V. M. Ustinov, S. S. Ruvimov, M. V. Maximov, P. S. Kop'ev, Z. I. Alferov, U. Richter, P. Werner, U. Goesele, and J. Heydenreich, "Low threshold, large T_0 injection laser emission from InGaAs quantum dots," *Electron. Lett.*, vol. 30, no. 17, pp. 1416–1417, Aug. 1994.

[2] M. Sugawara*, Self-Assembled InGaAs/GaAs Quantum Dots, Semiconductor and Semimetals*. New York: Academic, 1999, vol. 60.

[3] 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 $\mathrm{In}_{0.15}\mathrm{Ga}_{0.85}\mathrm{As}$ quantum well," *Electron. Lett.*, vol. 35, no. 14, pp. 1163–1165, Jul. 1999.

[4] P. G. Eliseev, H. Li, A. Stintz, G. T. Liu, T. C. Newell, K. J. Malloy, and L. F. Lester, "Transition dipole moment of InAs/InGaAs quantum dots from experiments on ultralow-threshold laser diodes," *Appl. Phys. Lett.*, vol. 77, no. 2, pp. 262–264, Jul. 2000.

[5] P. M. Varangis, H. Li, G. T. Liu, T. C. Newell, A. Stintz, B. Fuchs, K. J. Malloy, and L. F. Lester, "Low-threshold quantum dot lasers with 201 nm tuning range," *Electron. Lett.*, vol. 36, no. 18, pp. 1544–1545, Aug. 2000.

[6] T. Akiyama, M. Ekawa, M. Sugawara, K. Kawaguchi, H. Sudo, A. Kuramata, H. Ebe, K. Morito, and Y. Arakawa, "An ultrawide-band semiconductor optical amplifier having an extremely high penalty-free output power of 23 dBm achieved with quantum dots," *IEEE Photon. Technol. Lett.*, vol. 17, no. 8, pp. 1614–1616, Aug. 2005.

[7] P. Eliseev, H. Li, A. Stintz, G. T. Liu, T. C. Newell, K. J. Malloy, and L. F. Lester, "Tunable grating-coupled laser oscillation and spectral hole burning in an InAs quantum-dot laser diode," *IEEE J. Quantum Electron.*, vol. 36, no. 4, pp. 479–485, Apr. 2000.

[8] R. Alizon, D. Hadass, V. Mikhelashvili, G. Eisenstein, R. Schwertberger, A. Somers, J. P. Reithmaier, A. Forchel, M. Calligaro, S. Bansropun, and M. Krakowski, "Multiple wavelength amplification in wide band high power 1550 nm quantum dash optical amplifier," *Electron. Lett.*, vol. 40, no. 12, pp. 760–761, Jun. 2004.

[9] E. U. Rafailov, P. Loza-Alvarez, W. Sibbett, G. S. Sokolovskii, D. A. Livshits, A. E. Zhukov, and V. M. Ustinov, "Amplification of femtosecond pulses over by 18 dB in a quantum-dot semiconductor optical amplifier," *IEEE Photon. Technol. Lett.*, vol. 15, no. 19, pp. 1023–1025, Aug. 2003.

[10] D. Alexander, J. S. Deogun, and H. S. Hamza, "Quantum dot based technology for multiple wavelength conversion," in *Proc. LEOS 2005, 18th Annual Meeting of IEEE*, Oct. 2005, pp. 126–127.

[11] T. Akiyama, H. Kuwatsuka, T. Simoyama, Y. Nakata, K. Mukai, M. Sugawara, O. Wada, and H. Ishikawa, "Application of spectral-hole burning in the inhomogeneously broadened gain of self-assembled quantum dots to a multiwavelength-channel nonlinear optical device," *IEEE Photon. Technol. Lett.*, vol. 12, no. 10, pp. 1301–1303, Aug. 2000.

[12] Y. S. Su and C. F. Lin, "Anticompetition of laser modes in quantum dot lasers," in *Proc. CLEO 2005*, May 2005, vol. 3, pp. 1617–1673, Paper CThH5.