Extremely Broadband Superluminescent Diodes/Semiconductor Laser Amplifiers Using Nonidentical InGaAsP Quantum Wells

Bing-Ruey Wu[a], Ching-Fuh Lin*[a], Lih-Wen Laih[b] and Tien-Tsorng Shih[b]

[a] Department of Electrical Engineering and Graduate Institute of Electro-Optical Engineering, National Taiwan University ,Taipei 106, Taiwan

[b] Telecommunication Laboratory, Chunghua Telecom Co., Ltd., Yang-Mei, Taiwan

ABSTRACT

Extremely broadband emission is obtained from superluminescent diodes (SLDs)/semiconductor laser amplifiers (SLAs) with nonidentical quantum wells made of InGaAsP/InP materials. Two opposite sequences of nonidentical multiple quantum wells (MQWs), consisting of three $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ quantum wells (QWs) and two $In_{0.53}Ga_{0.47}As$ QWs, are designed, fabricated, and measured. Nonuniform carrier distribution inside MQWs is further verified experimentally. The sequence of those wells is shown to have a significant influence on the emission spectra, indicating that stacking nonidentical MQWs for bandwidth broadening is not intuitively straightforward. With the three $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ quantum wells near the n-cladding layer and two $In_{0.53}Ga_{0.47}As$ quantum wells near the p-cladding layer, all bounded by $In_{0.86}Ga_{0.14}As_{0.3}P_{0.7}$ barriers, the emission spectrum of the fabricated SLDs/SLAs could cover from less than 1.3 μm to over 1.55 μm. The spectral width is near 300 nm.

Keywords: nonidentical multiple quantum wells, nonuniform carrier distribution, broadband emission, superluminescent diode.

1. INTRODUCTION

Broadband characteristics of superluminescent diodes/semiconductor laser amplifiers are useful for optical communication and spectroscopy. Utilizing contemporary technologies, optical fiber can have extremely broad bandwidth of tens of THz. However, the abundant bandwidth of opical fiber is not fully exploited in modern optical communication system due to the limited bandwidth of the EDFA's, which are utilized in most contemporary communication systems but have the bandwidth no more than 80nm (C-band: 1530-1565nm; L-band: 1570-1610nm).[1] Other amplifiers like Raman amplifiers and semiconductor laser amplifiers (SLA's) are also considered in the optical communication system. SLAs have the advantages

*Correspondence: Email: cflin@cc.ee.ntu.edu.tw; Tel: 886-2-23635251 ext. 339; Fax: 886-2-23638247

Optoelectronic Interconnects VIII, Suning Tang, Yao Li, Editors, Proceedings of SPIE Vol. 4292 (2001) © 2001 SPIE · 0277-786X/01/$15.00

of compact size, direct integration with electronics, and so on. However, their bandwidth is usually less than 50 nm. Although the entire bandwidth of optical fiber could be possibly covered by several SLA's with different spectral ranges, the opical communication system will then becomes quite complicated. Therefore, if the bandwidth of SLA's could be broadened, they will be even more attractive.

On the other hand, for spectroscopy measurement, broadband characteristics are also important. For example, if the gain spectrum of the SLD's/SLA's is wide in dual-wavelength semiconductor lasers,[2.] the lasing wavelengths of the external-cavity semiconductor laser could be separated far enough for complete optical measurement, such as in optical fiber characteristics measurements, biochemical experiments, etc.

Multiple quantum well (MQW) engineering is a convenient way that had been widely used to broaden the SLA's/SLD's bandwidth. The scheme includes using simultaneous transitions of n = 1 and n = 2 states[3] in a quantum well and stacking multiple quantum wells (MQWs) of different widths.[4, 5.] Because the simultaneous transitions of n = 1 and n = 2 energy states in identical QWs strongly rely on the device length[3], using nonidentical MQWs' had attracted more attention due to its flexibility of design. However, recent researches had theoretically[6] and experimentally[7, 8] discovered that the carrier distribution among the MQWs is not uniform. The experimental evidence was indirectly obtained from characteristics of laser diodes, which indicates that stacking nonidentical MQWs for bandwidth broadening is not intuitively straightforward.

In this work, we report the direct observation of emission spectra from SLA's/SLD's that are strongly influenced by the well sequence of the nonidentical MQWs as a result of nonuniform carrier distribution. This paper is organized as follows. After this section of introduction, Section 2 reports the design, fabrication, and characteristics measurement of nonidentical MQWs for broadband SLAs/SLDs. Section 3 discusses the properties from optical measurement of the fabricated devices. The study shows that extremely broadband emission is only possible with properly designed sequence of nonidentical MQWs. For nonidentical MQWs made of InGaAsP/InP materials, the emission bandwidth could cover from 1.3μm to 1.55μm when the two $In_{0.53}Ga_{0.47}As$ QWs are grown near the n-cladding layer, while the three $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ QWs are grown near the p-cladding layer.

2. EXPERIMENT

2.1 Designs and Fabrication for Nonidentical MQW

MQWs with calculated transition energy corresponding to wavelength 1.3μm and 1.55μm are designed to compose the active layer. The designed nonidentical MQW structures are shown in Fig. 1. The detailed transition wavelengths calculated using Luttinger-Kohn model[9] of $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs are 1.30μm, 1.24μm; and those of $In_{0.53}Ga_{0.47}As$ double QWs are 1.54μm, 1.46μm, and 1.18μm. Both barriers and separate-confinement heterostructure (SCH) regions consist of $In_{0.86}Ga_{0.14}As_{0.3}P_{0.7}$, and their lengths are 15nm and 120nm, respectively. The only difference between Substrate I and II is the mirror-imaged quantum well sequence. These mirror-imaged nonidentical MQW structures enable direct observation of the carrier distribution inside the MQW structure. Note that the designed layer structures are lattice matched to InP substrate

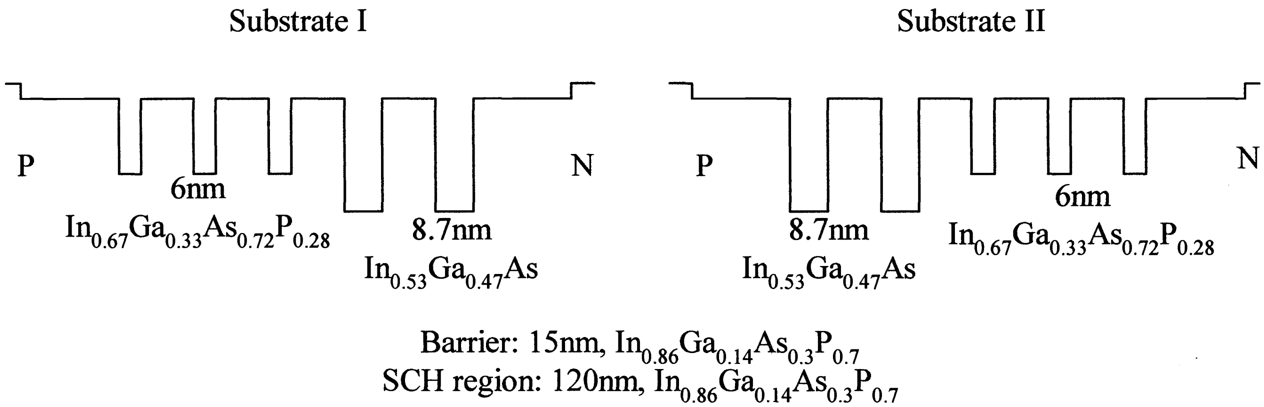

Fig. 1 Layer structures of substrate I and substrate II.

without tensile or compressive strain, excluding their influences on material parameters. Designed layer structures are grown on InP substrate using metal-organic chemical vapor deposition (MOCVD). Bent ridge-waveguide SLDs/SLAs are fabricated using standard processing procedure. Bent waveguide structure can eliminate optical feedback between the facets of devices[10], resulting in amplified spontaneous emission, rather than Fabry-Parot resonance. Ridge waveguide is 5μm wide and is created by electron cyclotron resonance-reactive ion etch (ECR-RIE). Etching was stopped at ~100nm above the SCH layer. The devices are about 500μm long. The fabrication is completed by n-contact metallization and then the devices were cleaved apart. No facet coatings were applied to the devices.

2.2 Characteristics Measurement of Fabricated Devices

Optical characteristics of substrate I and II such as SLD spectrum under different current levels and light-current relations are measured and shown in Fig. 2 and 3, respectively. Very distinct features of the emission spectra and the L-I characteristics of the two samples are clearly shown. In Fig. 2 (substrate I), the emission at low injection current occurs at the wavelength corresponding to the n=1 transition of $In_{0.53}Ga_{0.47}As$ double QWs, namely 1.55μm, which are close to the n-cladding layer. When the injection current increases, the emission spectrum is first broadened due to the simultaneous transition of n=1, 2 states in such wells. The emission contribution from the $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ QWs is not obvious until the injection current is above 400mA. Beyond 400mA, $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs further broaden the emission spectra. The spectral width of substrate I is effectively broadened under this sequence of nonidentical MQW. The broadest spectrum at 600mA covers from less than 1.3μm to more than 1.55μm, with the spectral width of 285.5nm. The broadened spectrum implies more uniform carrier distribution inside the MQW structure under the same current level, which means much less gain under the QW condition. Thus the penalty of the extremely broadband properties of substrate I is the degraded L-I characteristics.

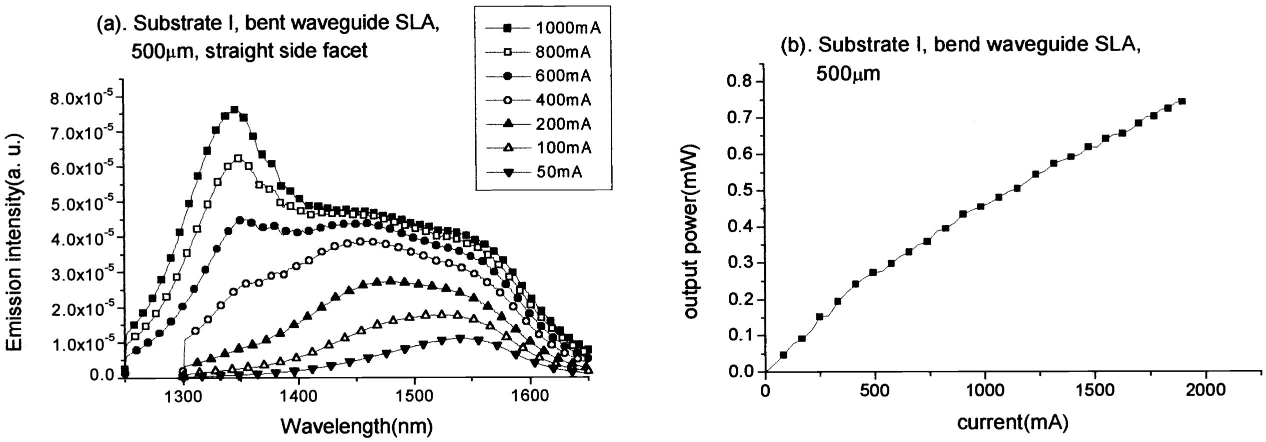

Fig. 2 Measured (a) Emission spectrum under different current level, (b) L-I characteristics of substrate I

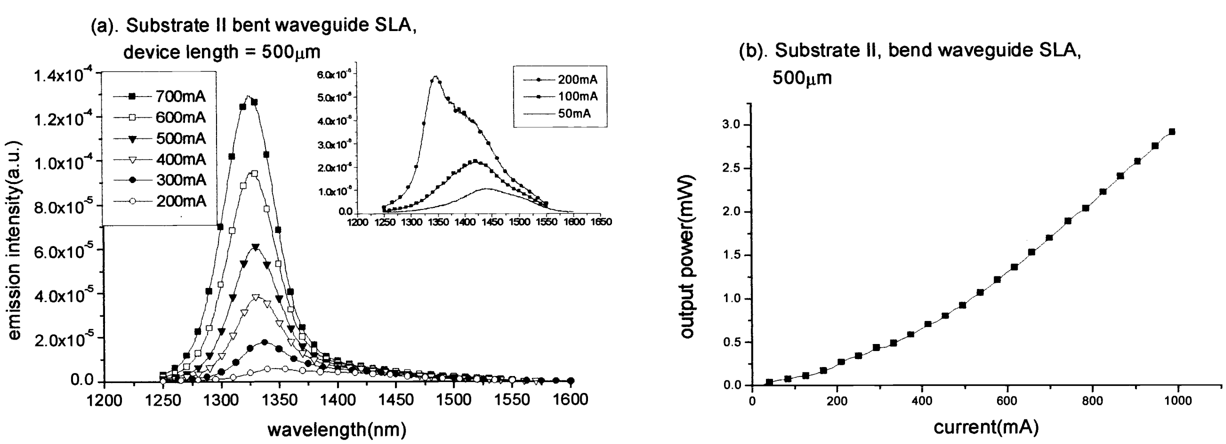

Fig. 3 Measured (a) Emission spectrum under different current level, (b) L-I characteristics of substrate II

For substrate II, the emission at injection current less than 200mA occurs at wavelength corresponding to near the n=1 transition of the $In_{0.53}Ga_{0.47}As$ QWs. With the injection current increases over 200mA, the emission spectrum shifts to the wavelength corresponding to the $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs, which are near the n-cladding layer. Further increase of the injection current does not obviously change the emission spectra. Emission from $In_{0.53}Ga_{0.47}As$ double QWs barely affects the spectra under high current injection, so the emission spectra of substrate II with current over 200mA act as SLAs with normal MQW structures. The spectral width is about 53nm under high current. The maximum spectral width happens at 50mA with 139.5nm, showing the effects of emission from both $In_{0.53}Ga_{0.47}As$ double QWs and $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs. The L-I characteristics of substrate II is much better than that of substrate I, showing the more concentrated carrier distribution inside the $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs. Note that for the two samples, emissions from QWs near the n-cladding layer dominate. This may suggest the electron-dominated carrier distribution. Spectral width under different current levels of both substrates II and I are shown in Fig. 4 for comparison. Referring to Fig. 2, the emission from the 1.3μm double QWs increases with the increasing current, leading to the convex property in the spectral width-current plot for substrate I. No significant change in spectral width of substrate II with current over 200mA is observed, showing tremendous discrepancy in the two substrates.

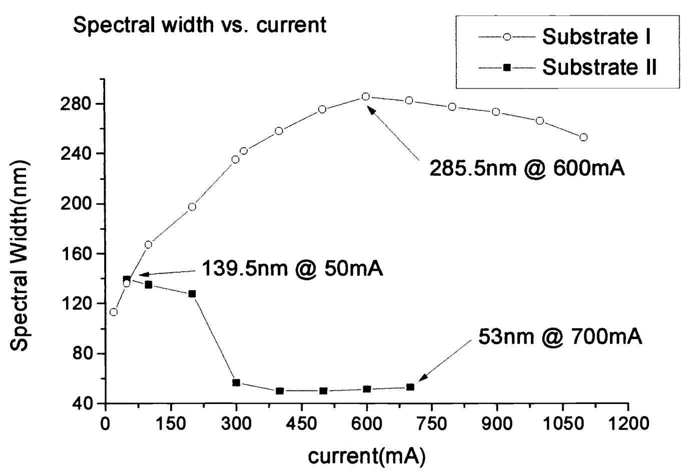

Fig. 4 Spectral width of substrate II and I under different current injection level

3. DISCUSSIONS

The emission characteristics shown in Fig. 2 and 3 are apparently related to the sequential capture of carriers into the MQWs. The sequence of MQWs influences the carrier distribution, so the devices have the emission spectrum corresponding to carrier density in each well. In order to explain the measured difference in spectra and L-I characteristics, carrier transport effect, uniformity of carrier distribution inside nonidentical MQW structure, and properties of gain under different carrier density in each sets of QWs are discussed in order.

3.1 Carrier Transport Effect

Due to the quantized nature of the QWs along the epitaxial axis, complicated carrier dynamics are involved therein. The dynamics include carrier transport in three-dimensional (3D) unquantized structures as well as carrier capture/emission processes between 3D and 2D carriers. When the devices are forward biased, electrons inject from the n-cladding layer and holes inject from the opposite side of the MQW structures. Contemporary models describing carrier dynamics involve classical carrier diffusion/drift across the unquantized 3D structure, and the process by which carrier are captured into the QW and by which they escape from the QW.[10, 11] The rate of classical diffusion/drift of electron and hole depends on material parameters, and the carrier capture rate into QWs is determined by density of state (DOS) of QWs. These processes all cause time delays, which will affect the final carrier distribution and the dynamic properties of devices. The measured spectra show that the QWs near the n-cladding layer dominate the carrier distribution process regardless of the emission wavelength. Substrate I has the emission spectrum dominated by $In_{0.53}Ga_{0.47}As$ double QWs and substrate II has it dominated by $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs. This observation shows different behaviors from other reports.[12, 13] The reason is due to the wide SCH layer, leading to the effect of electron transport more significant than the effect of electron capture time. When the total time delays of electron transport (including diffuse/drift and capture) are shorter than that of hole, electron will be captured into QW 2D states faster than hole, causing electron-dominated carrier distribution. In the mean time, hole will distribute according to the distribution of electron in order to maintain charge neutrality. This result in higher carrier distribution density in the QWs near the n-cladding layer and will cause the emission dominated by QWs near the n-cladding layer. It also should be noted that the uniformity of carrier distribution inside the MQWs is not the same for the two sequences, which will be discussed below.

3.2 Uniformity of Carrier Distribution inside nonidentical MQW structure

From Fig. 2 and 3, more uniform carrier distribution of substrate I than substrate II is clearly observed. The uniformity of carrier distribution inside the MQW structures is determined by the injection of dominant carrier and the ability to capture carriers in of each QW. The carrier distribution will be more concentrated if the QW near the dominant carrier side (n- or p-cladding side) is more able to confine carrier. On the other hand, the carrier distribution will be more uniform if the QW is more incapable of capturing carriers. From section 3.1, the ability for the QW to capture carriers is proportional to the 2D density of state. The relation between 3D unconfined DOS and the step-like 2D DOS of QW are illustrated in Fig. 5. The 2D and 3D DOS's approach the same value at the energy equal to the QW transition energy. Table I is the calculation result of n=1 transition energy and effective mass of the two sets of MQWs used in substrates I and II.

Table I The n=1 transition energy and effective mass of electron and heavy hole of the two sets of QWs

The emission wavelength designed	1.55μm	1.3μm
Quantum well material	$In_{0.53}Ga_{0.47}As$ (Double QWs)	$In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ (Triple QWs)
Quantum well width	87Å	60Å
Emission wavelength from our simulation	1.54μm	1.3μm
1^{st} quantized state of conduction band	53.22meV	52.58meV
1^{st} quantized state of valence band	9.17meV	14.34meV
Conduction band effective mass	$0.041m_0$	$0.052\ m_0$
Valence band effective mass(Heavy hole)	$0.42\ m_0$	$0.47\ m_0$

The first quantized states above the band edge of the two sets of QWs are almost the same due to the width and well-barrier structure of the QWs. Thus the final 2D DOS is solely determined by effective mass of carriers, which is an intrinsic material parameter. Although the valence band DOS is not perfectly parabolic, the schematic likes Fig. 5 could be drawn to explain qualitatively: For $In_{0.53}Ga_{0.47}As$ grown lattice-matched to InP substrate, the effective masses of electron and hole are smaller than $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ on lattice-matched InP substrate. Since effective mass indicates the curvature of 3D DOS of bulk material, 3D DOS of $In_{0.53}Ga_{0.47}As$ is smaller than $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ under the same energy. This means the smaller 2D DOS of the 87Å double $In_{0.53}Ga_{0.47}As$ QWs than that of the 60Å triple $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ QWs. Therefore, the 60Å triple $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ QWs have stronger ability to confine carriers than 87Å double $In_{0.53}Ga_{0.47}As$ QWs.

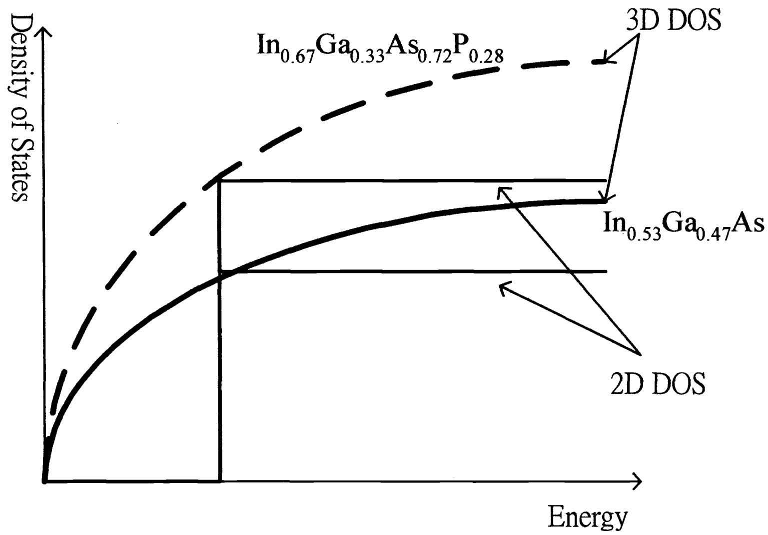

Fig. 5 Schematic diagram showing the 3D and 2D DOS of the two sets of QWs

Combining the ability of capturing carriers with the injection of dominant carriers, the difference in uniformity of carrier distribution between the two substrates can be explained as follows. When electron, the dominant carrier of both samples, injects from n-cladding layer, it first encounters $In_{0.53}Ga_{0.47}As$ QWs and $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ QWs in substrates I and II, respectively. Due to the superior ability to capture carrier for $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ QWs, electron cannot distribute uniformly among the MQW structures in substrate II. On the contrary, electron in substrate I can distribute more freely because of the inferior ability of $In_{0.53}Ga_{0.47}As$ QWs to confine carrier. After electron has reached the steady state of distribution, hole distributes according to electron distribution, resulting in more uniform carrier distribution, hence more broadened spectrum for substrate I than for substrate II. There is a tradeoff between more broadened emission spectrum and debased light-current characteristics based on carrier distribution.

3.3 Carrier Density vs. Peak Gain

In order to explain the spectral behavior of the two samples, detailed simulations using Luttinger-Kohn Hamiltonian[9] to acquire gain spectra, spontaneous emission spectra are performed individually on $In_{0.53}Ga_{0.47}As$ double QWs (with wavelength 1.55μm) and $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs (with wavelength 1.3μm). Afterward the peak gain values under certain carrier density in each well are extracted and plotted as Fig. 6. The inset shows the condition for $In_{0.53}Ga_{0.47}As$ and $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ single QW. From the inset the conclusion that $In_{0.53}Ga_{0.47}As$ single QW has higher gain than $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ single QW under all carrier concentrations can be made. This is because more separated quasi-Fermi level is required for shorter wavelength emission. If the well number of each kind is the same, the emission at 1.3μm will be negligible due to its much less gain. Nevertheless, if the well numbers are not equal, the relation of gain vs. carrier density varies. In Fig. 6 under low carrier density, the gain of 1.55μm double QWs is higher than that of 1.3μm triple QWs. However, the gain of 1.3μm triple QW increases faster than 1.55μm double QW due to the one more layer of QWs, which aggravates the gain inside MQW. Therefore over a certain 3D carrier density (which equals 2D carrier density divided by QW well width), the gain of 1.3μm triple QWs surpasses the gain of 1.55μm double QWs. Using the properties described above, the measured emission spectra could be explained as follows. For substrate I, although gain occurs at lower carrier density for $In_{0.53}Ga_{0.47}As$ double QWs, corresponding to the emission spectrum under low injection current level, the increasing rate of peak gain of $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs is larger than that of $In_{0.53}Ga_{0.47}As$ double QWs. Therefore, the two kinds of MQWs have almost equal gain at a particular injection level, leading to the broadened spectrum as a result of the superposition of the gain spectrum of the two types of MQWs. The injection level of almost equal gain of sample A is 600mA. After 600mA, gain of $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs surpasses $In_{0.53}Ga_{0.47}As$ double QWs, resulting in the emission domination of $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs with wavelength ~1350nm.

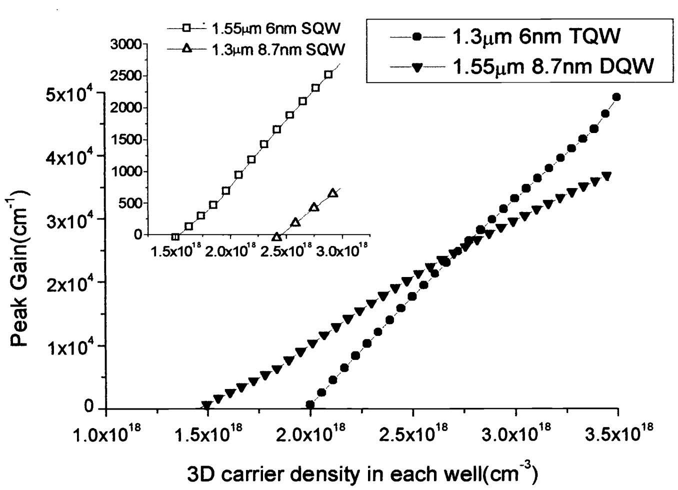

Fig. 6 Calculated peak gain vs. 3D carrier density in each well for $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs and $In_{0.53}Ga_{0.47}As$ double QWs. The inset shows the single QW situation.

For substrate II under low injection current level, detailed plot shows the emission wavelength ~1450nm, corresponding to the superposition of the gain spectra of $In_{0.53}Ga_{0.47}As$ double QWs and $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs. This is due to the higher gain of $In_{0.53}Ga_{0.47}As$ double QWs than that of $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs even when carrier density is smaller in 1.55μm QWs than that in 1.33μm QWs at a given injection level. Further increase of injection current contributes only to the emission of $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs. The reason is that carrier accumulates more in the $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs than in $In_{0.53}Ga_{0.47}As$ double QWs due to the different ability in capturing carriers.

4 CONCLUSION

Different well sequences of nonidentical MQW structures are designed and used to fabricate SLDs/SLAs. The measured optical characteristics show significant influences of well sequence on the SLD/SLA properties. Stacking nonidentical MQWs to broaden the spectral width of SLAs/SLDs is not intuitively straightforward. Factors such as active layer material, MQW layer structure, QW numbers, gain spectra calculation and carrier dynamics must be taken into account. Extremely broadband SLDs using properly designed 8.7 nm $In_{0.53}Ga_{0.47}As$ double QWs and 6nm $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QWs were fabricated. The record spectral width is as large as 285.5nm, which covers from 1.3μm to 1.55μm. Further broadening of spectral width of SLAs/SLDs are feasible and under progress. Fine tuning of MQW structures to minimize the injection current for the maximum bandwidth is possible by deploying various techniques, such as adjusting the SCH region of either side.

REFERENCES

1. Stern, T. E. and Bala, K. *Multiewavelength Optical Networks*, Chap. 4, pp. 193-199, Addison-Wesley, MA, 1999.
2. C. F. Lin, B. L. Lee, and M. J. Chen, "Wide range tunable dual-wavelength semiconductor laser using asymmetric dual quantum wells ,*IEEE Photon. Technol. Lett.,* vol. 10, pp. 1208-1210, 1998.
3. A. T. Semenov, V. R. Shidlovski, and S. A. Safin, "Wide spectrum single quantum well superluminescent diodes at 0.8mm with bent optical waveguide", *Electron. Lett.*, vol. 29, pp. 854-857, 1993.
4. C. F. Lin and B. L. Lee, "Extremely broadband AlGaAs/GaAs superluminescent diode", *Appl. Phys. Lett.*, vol. 71, pp. 1598-1600, 1997.
5. M. J. Hamp, D. T. Cassidy, B. J. Robinson, Q. C. Zhao, and D. A. Thompson, "Nonuniform carrier distribution in asymmetric multiple-quantum-well InGaAsP laser structure with different numbers of quantum wells", *Appl. Phys. Lett.*, vol. 74, pp. 744-746, 1999.
6. N. Tessler and G. Eisenstein, "On carrier injection and gain dynamics in quantum well lasers", *IEEE J. Quantum Electron.*, vol. 29, pp.1586-1595, 1993.
7. B. L. Lee, C. F. Lin, J. W. Lai, and W. Lin, "Experimental evidence of nonuniform carrier distribution in multiple-quantum-well laser diodes," *Electron. Lett.*, vol. 34, pp. 1230-1231, 1998.
8. H. Yamazaki, A. Tomita, and M. Yamaguchi, "Evidence of nonuniform carrier distribution in multiple quantum well

lasers", *Appl. Phys. Lett.*, vol. 71, pp. 767-769, 1997.

9. Chuang, S. L., *Physics of Optoelectronic Devices*, Chap. 5, 9, John Wiley & Sons, New York, 1995.

10. Alphonse, G. A., Gilbert, D. B., Harvey, M. G. and Ettenberg, M. "High-power superluminescent diodes", *IEEE J. Quantum Electron.*, vol. 24, pp. 2454-2457, 1988.