Anticompetition of Laser Modes in Quantum Dot Lasers

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ABSTRACT

Laser mode competition is a well-known phenomenon in a multi-mode laser system. The competition between different lasing modes is considered inevitable in all kinds of lasers. However, our experiments show that laser mode anti-competition can be observed in lasers that combine either quantum dots (QD) of different sizes or quantum wells of different composition and width. Here we report the anti-competition experiment from QD lasers. The QD structure is grown on a GaAs substrate. Two types of QD layers for 1.24μm emission and 1.28μm emission are grown alternatively in the active layer. The anti-competition behavior is observed in an external cavity laser controlled by the grating, oscillating at two different wavelengths. Experimental results show that when short-wavelength light intensity increases, long-wavelength light intensity will also increase. This is the anti-competition behavior. Nonetheless, when short-wavelength light intensity is above a certain level, long-wavelength light intensity decreases. It means that the laser behavior changes to the usual competition situation at the large intensity.

Keywords: anticompetition, competition, quantum-dot (QD) laser, multiple quantum-wells (MQWs) laser, semiconductor laser

1. INTRODUCTION

The gain bandwidth of semiconductor lasers can be increased to over 200nm by several ways like combining first and second quantized states of a single QW[1, 2], combining quantum wells of different composition and width[3] as well as utilizing the first and second quantized states of quantum dots[4]. When the pumping level is above threshold, different modes will start oscillating. With the fixed pumping power, different modes will compete for the available gain. An oscillation existing in one mode tends to suppress the oscillation in another mode. Competition phenomenon has been analyzed

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soon after the invention of the laser systems[5]. The significance of competition appears in several circumstances, such as the switching time between modes[6], electro-optical logic operation[7], and data inversion[8]. The gain competition between different lasing modes is considered as an inevitable phenomenon for almost all kinds of lasers. However, experiments show that anti-competition behaviours can be observed in lasers with quantum dot of different sizes or quantum wells of different composition and width[9]. In this section, we briefly introduce previous anti-competition experiments in semiconductor laser using MQWs.

1.1 Broadband gain medium[10]

The laser-mode anti-competition was first discovered in a dual-wavelength laser system with the gain medium consisting of non-identical multiple quantum wells. In a dual-wavelength laser system with single gain medium, the tuning range is usually limited by the bandwidth of the gain medium. In order to obtain large spectral separation for the two lasing wavelengths, one needs a broadband gain medium. The gain medium chosen for anti-competition experiments in QW lasers is a non-identical InGaAsP QW structure, combining 8.7-nm $In_{0.53}Ga_{0.47}As$ double QW, and 6.0-nm $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QW. The calculated transition wavelengths corresponding to the bounded energy states of the non-identical MQWs are listed in Table 1. The maximum tuning range is then achieved to 174-nm, with short-wavelength at 1355-nm and long-wavelength at 1530-nm, respectively. Based on this gain structure, the dual-wavelength separation of anti-competition experiments is tuned to maximum of 170-nm.

Table 1 Calculated transition wavelengths

energy state (n)	8.7-nm $In_{0.53}Ga_{0.47}As$ Double QW (μm)	6.0-nm $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ Triple QW (μm)
1	1.54	1.3
2	1.46	1.24
3	1.18	unbounded

1.2 Anti-competition in QW lasers[9, 11]

With the broadband gain medium, the dual-wavelength separation in the anti-competition experiments could be tuned from 30-nm to 170-nm. The experimental setup is shown in Figure 1. The QW structure of the gain medium is described previously. The gain medium is actually an uncoated Fabry-Perot laser diode (FPLD) with the device length of 300-um. The uncoated FPLD has the threshold current at 143mA. In the grating-loaded external cavity, the lasing wavelength can still be controlled as the operation current is not much larger than the threshold current. Therefore, most of the experiments were done at 146mA.

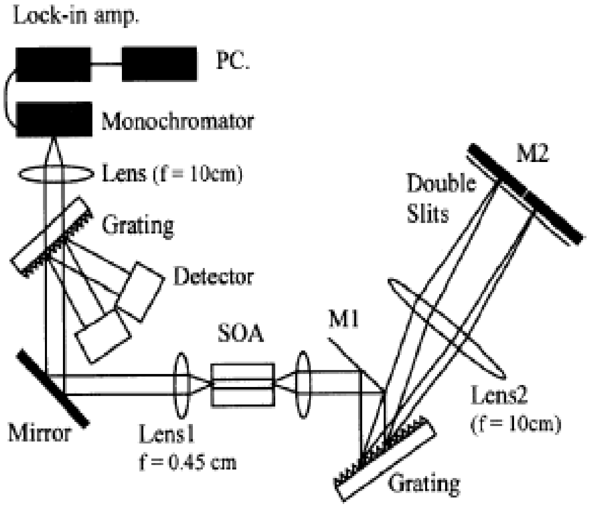

Fig.1 Experimental setup of anti-competition in QW lasers (After Ref 10, 11)

Anti-competition behavior is measured by using two gratings to select specific wavelengths. The right-hand side grating separates the collimated light from the device. Lens 2 then collimates the separated wavelengths to parallel dispersed light. A double-slit with variable slit separation is placed in front of a reflected mirror to choose specific wavelength separation. In the experiment, five wavelength separations have been experimented. They are 30-nm, 60-nm, 130-nm, 150-nm, and 170-nm, respectively. The left-hand side grating is used to separate the output light at the two selected wavelengths. After the grating, two InGaAs photodiodes are used to measure the light powers of the two wavelengths separately. The anti-competition behaves in different manners, depending on the operation conditions. The influential factors for anti-competition include wavelength separation, wavelength position, initial power of long-wavelength mode, power of the short-wavelength mode, and injection current.

Wavelength separation is important for the occurrence of anti-competition. When the two wavelengths are widely separated, their gains greatly differ. In some situations, the gain of the long-wavelength mode is just above threshold and that of the short-wavelength mode is far above threshold. In this case, the long-wavelength mode hardly oscillates. Competition then does not occur. However, due to the mechanism of optical pumping, the short-wavelength mode can provide the long-wavelength mode with some optical gain. As a result, the long-wavelength mode increases its intensity with the intensity of the short-wavelength mode. This is the anti-competition behavior.

Anti-competition also behaves differently for different wavelength position even at fixed wavelength separation. The gain is different at different wavelength position. As a result, for the position of long-wavelength mode at higher gain profile, optical pumping can offer more optical gain to the long-wavelength mode. The behavior of anti-competition is then more obvious.

Initial power of long-wavelength mode is another influential factor. The gradient of curve of the anti-competition and the maximum long-wavelength mode power increment both increase with decreasing initial long-wavelength mode power. When the initial power of long-wavelength mode is low, the long-wavelength mode takes up low portion of the system gain. The available short-wavelength mode gain will become large. As a result, the gradient of anti-competition curve becomes steeper and the maximum long-wavelength mode power increment is larger.

The fourth factor is the power of the short-wavelength mode. Anti-competition exists only when the power of the short-wavelength mode is below a certain level. Experiments show that anti-competition exists only when the short-wavelength mode is below 0.07mW.

The final influential factor is injection current. To avoid the influence of Fabry-Perot mode, the injection currents for the experiment, 146mA and 149mA, are only slightly above the threshold. In general, increasing the injection current elevates total gain. In addition, increasing the injection current will cause an increase in temperature, which may lead to the increase of the gain for short-wavelength mode and the decrease of the gain for long-wavelength mode. The reason is due to strongly temperature-dependent Fermi-Dirac distribution, which favors carriers in high-energy at large temperature. Therefore, the gain increment of short-wavelength mode is larger than that of long-wavelength mode when one increases the injection current.

In brief, anti-competition had been discovered in lasers with non-identical MQWs. The gain medium used for anti-competition experiment is a non-identical InGaAsP QW structure, combining $In_{0.53}Ga_{0.47}As$ double QW, and $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ triple QW. The anti-competition could exist for dual-wavelength operation with spectral separation from below 100 nm to 170 nm.

2. QUANTUM-DOT LASERS for ANTI-COMPETITION

2.1 Epi-structure of quantum dots used in the experiment

The semiconductor quantum dot epi-structure is based on GaAs substrate. InAs QDs are embedded in $In_{0.15}Ga_{0.85}As$/GaAs QWs. p-type $Al_{0.35}Ga_{0.65}As$ is used as hole injection layer and n-type $Al_{0.35}Ga_{0.65}As$ as electron injection layer. The bandgap difference between GaAs barrier and $Al_{0.35}Ga_{0.65}As$ carrier injection layer makes carriers confined within the active layer. In addition, the dielectric constant difference between the two materials confines the optical power. The whole epi-structure is listed in Table 2.

Table 2 Wafer Structure

Material	Group	Repeat	Mole fraction(x)	Thickness (nm)	Doping	Type	Dopant
GaAs				100	5e19	P	C
Al(x)Ga(1-x)As			0.35~0	20	3e18	P	C
Al(x)Ga(1-x)As			0.35	700	1e18	P	C
Al(x)Ga(1-x)As			0.35	500	5e17	P	C
GaAs	2	5		35		U/D	
In(x)Ga(1-x)As	2	5	0.15	5		U/D	
InAs(for 1.24um)	2	5		0.7		U/D	
GaAs	2	5		35		U/D	
In(x)Ga(1-x)As	2	5	0.15	5		U/D	
InAs(for 1.28um)	2	5		0.8		U/D	
GaAs				35		U/D	
Al(x)Ga(1-x)As			0.35	500	5e17	N	Si
Al(x)Ga(1-x)As			0.35	1000	1e18	N	Si
Al(x)Ga(1-x)As			0~0.35	20	3e18	N	Si
GaAs				500	3e18	N	Si
GaAs substrate	N+ GaAs 3inch						

2.2 Fabrication of quantum dot optical amplifiers and quantum dot lasers

Laser diodes and optical amplifiers are fabricated on the wafer with the above QD epi-structure. The fabrication process includes waveguide fabrication, passivation dielectric growth, p-contact metallization, lapping and n-contact metallization. These devices use double channel waveguide. The channels are etched by HBr:H_2O_2:HCl:H_2O solution with AZ5214E photoresis as the etching mask. The width of waveguide is 2.3μm. The etched depth is 100nm~200nm above the undoped GaAs barrier. The passivation dielectric is silicon dioxide deposited by PECVD at 300°C. Due to the small dimension of waveguide width, a self align procedure is developed to define the region of which oxide is removed. The electrical contact on p-type GaAs is Ti/Pt/Au 1kA/1kA/3kA followed by rapid thermal annealing. After p-contact metallization, the wafer is lapped down to 100μm. AuGe/Ni/Au is used as contact on n-GaAs substrate. Figure 2 shows the process flow chart. The black-color bar indicates the position of quantum dot layer. The light-gray color is PECVD grown oxide. The charcoal color is p-contact metal, and the black-dot bar is the n-contact metal.

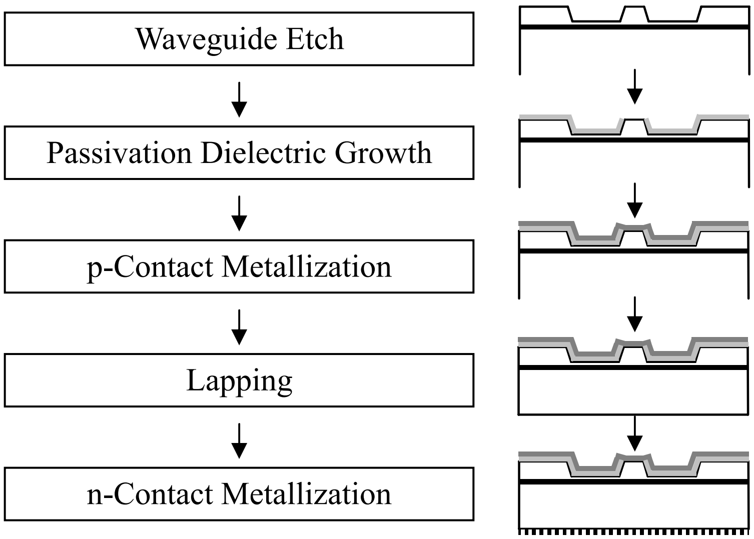

Fig.2 Process flow chart

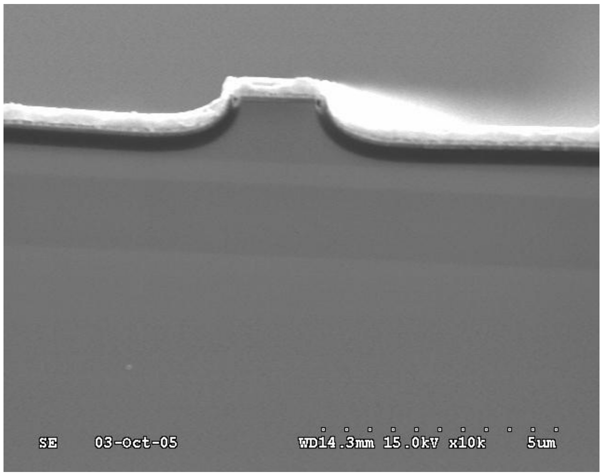

Fig.3 Cross section view of the fabricated device

2.3 Device characteristics

Figure 4 shows the emission spectra of the QD semiconductor optical amplifier (SOA) with a tilted waveguide. Device length is 350μm. The peak emission intensity of first quantized states is at 1.25μm. The peak emission intensity of second quantized states is at 1.17μm. Due to inhomogeneous broadening caused by dot size distribution, which large dots contributes to 1.28μm and small ones contributes to 1.24μm in the first quantized state, the EL emission spectrum covers more than 200nm wavelength. Figure 5 is the light output power versus current characteristic of a Fabry-Perot laser diode (FPLD) with the device length of 613μm. The operation temperature is controlled at 26.7°C. The threshold current is 15.7mA, and the calculated light – current slope is 0.26mW/mA.

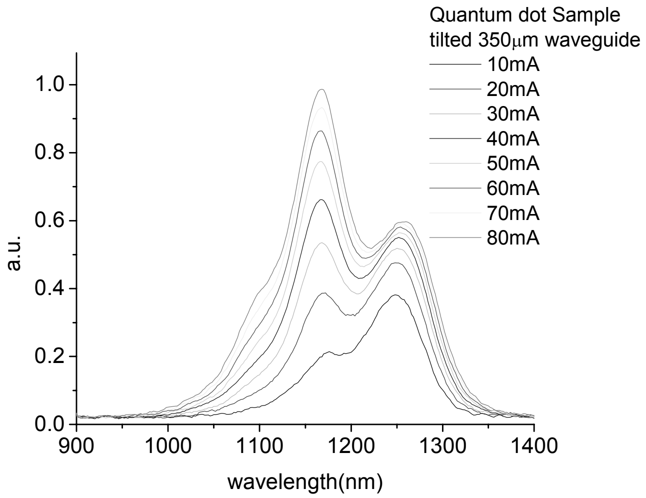

Fig.4 EL spectrum of a QD device with tilted waveguide

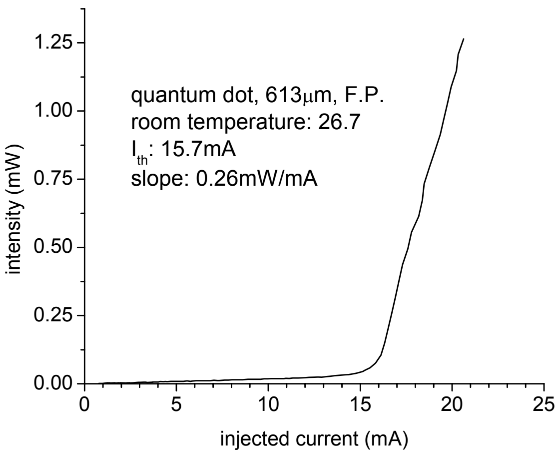

Fig.5 light output power vs. current in device with straight waveguide

3. EXPERIMENT OF ANTI-COMPETITION IN QUANTU-DOT LASERS

3.1 Experimental set up of external cavity

The anti-competition behavior is observed in an external cavity laser schematically shown in Figure 6. The external cavity uses two mirrors and grating 1 to control the oscillation wavelengths. Such a cavity configuration could make the laser oscillate at two different wavelengths. This external-cavity laser uses a FPLD fabricated on the QD substrate as the gain medium. The device with a length of 613μm. The light output power versus current characteristic is shown in Figure 5. The operating wavelength is tuned to oscillate at two wavelengths simultaneously. One is at 1262.3nm, corresponding to the first quantized state, and the other is at 1168.5nm, corresponding to the second quantized state. In Figure 5, gray line indicates the optical path of 1262.3nm light, while black line is for the optical path of 1168.5nm light. Lights of the two wavelengths are separated by grating 1 and reflected back to the FPLD by two mirrors. The feedback efficiency of 1262.3nm light is optimized and then fixed at the optimum. Tilting Mirror 2 in vertical direction varies the feedback efficiency of 1168.5nm light. Then the optical power of 1168.5nm light is varied. Output power of the two wavelengths are separated by grating 2 and collected by two InGaAs photodiodes simultaneously. The light-output power curve is recorded with different feedback amount of the 1168.5nm light.

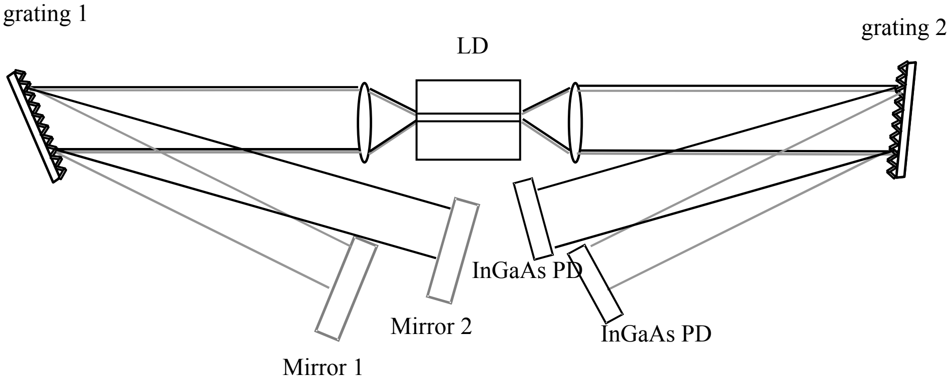

Fig.6 Two wavelength external-cavity configuration and setup for monitoring the power of both wavelengths

3.2 Behaviors of anti-competition in QD lasers

Figure 7 shows the recorded 1262.3nm wavelength power versus the 1168.5nm wavelength power. As the injection currents is 60mA, anti-competition is very weak. The output power of 1168.5nm wavelength only varies from zero to 1.5mW, depending on the feedback amount of 1168.5nm wavelength. As shown in Figure 7, when the output power of the 1168.5nm wavelength increases from 0.5mW to 1mW, the output power of 1262.3nm wavelength also increases by 0.15mW. As the injection current is increased to 65mA, the output power of 1168.5nm wavelength could vary from zero to 2mW.; while that of 1262.3nm wavelength could increase by 0.3mW. At this current level, anti-competition behavior is observed for a large range of 1168.5nm wavelength power.

When the injection current is further increased to 70mA, the curve is slightly different. The increase of 1262.3nm wavelength power with 1168.5nm wavelength power is faster. In the beginning, the output power of 1168.5nm wavelength power increases from 0.7mW to 1mW. The power of 1262.3nm wavelength increases by the amount of 0.36mW. The slope is larger than one. Then, the power of 1168.5nm wavelength increases from 1mW to 2mW. In this range, the curve changes to the competition situation. The power of 1262.3nm wavelength decreases by 0.02mW. As the power of 1168.5nm wavelength further increases from 2mW to 2.7mW. The curve changes back to anti-competition. The power of 1262.3nm increases by 0.1mW. After 2.7mW of the 1168.5nm wavelength power, the curve shows competition. The situation at the current level 75mA has the similar trends. Anti-competition occurs at first, with the slope larger than one. Then the curve changes to competition.

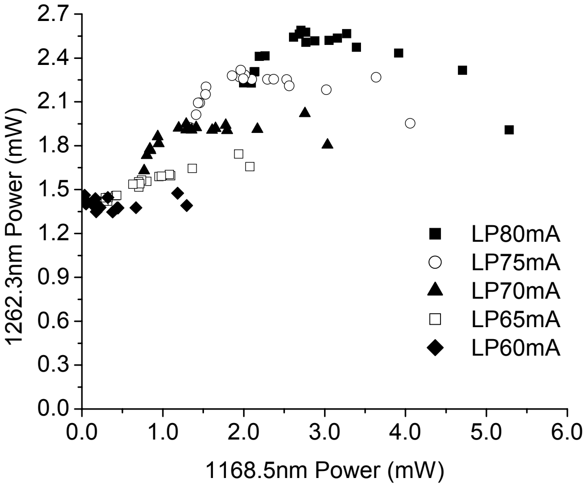

Fig.7 1262.3nm wavelength power vs. 1168.5nm wavelength power

The initial power of 1168.5nm wavelength for the curves of 70mA, 75mA, and 80mA is not zero due to the following reasons. In low injection current, when the ND-filter is tuned to the maximum loss, the output power of 1168.5nm wavelength could cease oscillation completely. As a result, the initial power of 1168.5nm in the curves of 60mA and 65mA is zero. As the current increases, the gain increment in the second quantized state arises rapidly. Then even when the ND-filter is tuned to the maximum loss, the mode around 1168.5nm wavelength still has enough gain to oscillate without any feedback provided by the external cavity. Therefore, the intensity of this mode causes the initial power of 1168.5nm wavelength not zero in the situation of 70mA, 75mA, and 80mA.

4. CONCLUSIONS

In conclusion, anti-competition effect is observed in a quantum-dot laser. The laser is operated at 1168.5nm and 1262.3nm wavelength simultaneously, corresponding to the second and the first quantized states of the quantum dots, respectively. The behavior of the anti-competition is observed when the power of the short-wavelength (1168.5nm) mode is controlled to vary. When the power at 1168.5nm wavelength increases the power of 1262.3nm also increases. However, anti-competition only occurs at the low optical power. As the power of the short-wavelength (1168.5nm) mode is beyond a certain level, depending on the injection current, the two oscillating modes become to have competition.

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