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1.3 μm p-Modulation Doped InGaAs/GaAs Quantum Dot Lasers with High Speed Direct Modulation Rate and Strong Optical Feedback Resistance

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Abstract: Aiming to realize high-speed optical transmitters for isolator-free telecommunication systems, 1.3 µm p-modulation doped InGaAs/GaAs quantum dot (QD) lasers with a 400 µm long cavity have been reported. Compared with the un-doped QD laser as a reference, the p-doped QD laser emits at ground state, with an ultra-low threshold current and a high maximum output power. The p-doped QD laser also shows enhanced dynamic characteristics, with a 10 Gb/s large-signal direct modulation rate and a 7.8 GHz 3dB-bandwidth. In addition, the p-doped QD laser exhibits a strong coherent optical feedback resistance, which might be beyond –9 dB.

Keywords: quantum dot laser; molecular beam epitaxy; p-modulation doping; optical feedback

1. Introduction

In telecommunication systems based on traditional quantum well (QW) lasers, optical isolators are indispensable devices. The external optical feedback caused by unlinked fiber facets and other reflective surfaces will cause a perturbation in the photon density in lasers, leading to a fluctuation in the carrier density and coherence collapse [1–3]. For nearly a decade, quantum dot (QD) lasers have been suggested as an alternative to QW devices to realize low-cost and isolator-free applications. Due to the behavior of three-dimensional carrier confinement, QD lasers show a stronger damping effect and a lower linewidth enhancement factor (α -factor), which contribute to the resistance of undesired optical feedback [4–7]. A representative work has reported on a 25 Gb/s error-free transmission with an integrated InGaAs/GaAs QD laser transmitter based on Si substrate without optical isolators for core input/output (I/O) applications [8]. Meanwhile, QD lasers have exhibited many superior properties, such as ultra-low threshold current density [9–11], high temperature stability and high working temperature [12,13].

In order to achieve QD lasers with high speed modulation, the cavity length of the device is usually short. As a trade-off, a short cavity length will cause greater cavity loss, making the device unable to emit at ground state. In addition, devices with short cavity length are found to be more sensitive to feedback than devices with long cavity length [14].

In this paper, we report InGaAs/GaAs QD Fabry–Perot (FP) edge-emitting lasers with a 400 μ m long cavity. Benefiting from the p-modulation doped in the active region of muti-layer InGaAs/GaAs



QDs, the gain has been enhanced, and the static and dynamic characteristics of the laser have been improved obviously. Compared with the un-doped QD laser as a reference, the p-doped device shows a 17 mA threshold current and over 23 mW maximum output power. Meanwhile, the p-doped device has a 7.8 GHz 3dB-bandwidth (f_{3dB}) and a clearly opened eye diagram under 10 Gb/s direct modulation. Furthermore, the p-doped device works normally under the –9 dB optical feedback, which is almost the maximum level for communication systems [15].

2. Materials and Methods

The devices in our study were grown on GaAs (100) substrates using a RIBER Compact-21 molecular beam epitaxy (MBE) system. The active region included eight layers of InGaAs/GaAs QDs. The density of InAs QDs for each layer was around 4.5×10^{10} cm⁻². Each InAs QDs layer was capped by a 4 nm In_{0.18}Ga_{0.82} As strain-reducing layer and a subsequent 40 nm GaAs spacer. For the un-doped device as a reference, the GaAs spacer was un-doped. For the p-doped device, the GaAs spacer was p-modulation doped with a 5×10^{17} cm⁻³ density. The devices were fabricated with standard lithography and dry etching. The FP cavities of the lasers had a ridge waveguide, with a 300 µm long and 3 µm wide cavity. More details about QD growth and device fabrication have been reported previously [16].

In order to study the optical feedback sensitivities of the devices, the coherent optical feedback system was set up, as Figure 1 schematically represents. To avoid unnecessary feedback, the antireflection-coated lensed fiber was used for output coupling. The optical feedback loop consisted of an optical circulator (OC), a polarization controller (PC) and a variable optical attenuator (VOA). The PC and VOA were used to adjust the polarization and intensity of the optical feedback. The whole system was implemented in the worst polarization state.



Figure 1. Schematic diagram of the coherent optical feedback system.

In this study, all measurements were carried out at room temperature.

3. Results and Discussion

3.1. P–I–V Curves

Figure 2 depicts the power–current–voltage (P–I–V) curves of devices in continuous wave (CW) mode. The un-doped device shows a threshold current of 31 mA, a slope efficiency of 0.24 W/A and a maximum output power of around 14 mW. Under the bias current of 65 mA, the un-doped device emits at a wavelength of 1215 nm, under the excited state. Compared with the un-doped device, the p-doped device shows a much improved performance. The threshold current of the p-doped device is only 17 mA, which is almost reduced by a half. The maximum output power and slope efficiency of the p-doped device are over 23 mW and 0.32 W/A, respectively, which are both significantly greater than those of the un-doped device. Under the bias current of 65 mA, the p-doped device emits at a wavelength of 1315 nm, which is under the ground state [17]. The small energy level interval of the valence band states in the QDs results in a broad distribution of holes within those states due to

thermal effects. The addition of p-doping in the active region of QDs could increase the probability of holes occupying the ground state of the valence band, increasing the ground state energy level mode gain. Due to the increase in gain caused by p-doping, the p-doped device with a very short cavity could emit at ground state [18]. Meanwhile, because p-modulated doping provides additional holes for closely spaced valence band levels and increases the occupation of additional valence band states for QDs, the p-doped device shows an enhanced emission linewidth [19].



Figure 2. The power–current–voltage (P–I–V) curves of the devices. (a) Un-doped device and (b) p-doped device. The insets show the optical spectra of devices under a 65 mA bias current.

3.2. Small-Signal Modulation Responses

The small-signal responses of devices are measured under the bias current of 65 mA. The responses are normalized at low frequency. Figure 3 shows the experimental results and fitting curves using the function below:

$$H(f) = \frac{1}{1 + (2\pi f \tau_p)^2} \frac{f_r^4}{(f_r^2 - f^2)^2 + (\gamma f/2\pi)^2}$$
(1)

where τ_p stands for the carrier transport delay. From the fitting curves, the damping rate (γ) and relaxation oscillation frequency (f_r) are extracted, which are both shown in Figure 3. The f_{3dB} of the un-doped device and p-doped device are 3.7 and 7.8 GHz, respectively. The p-doped device obtains a flat frequency response corresponding to the higher γ of 39.31 ns⁻¹, which is attributed to the strong damping characteristics of the p-doped QD active layers [20].



Figure 3. The small-signal responses and the fitting curves of devices. (**a**) Un-doped device and (**b**) p-doped device.

3.3. Eye Diagrams

The large signal response curves of devices under a direct modulation rate of 10 Gb/s were measured. The eye diagrams of the devices were captured by the Agilent 86100D (Agilent technologies Inc., Santa Clara, CA, USA) sampling oscilloscope. As Figure 4 exhibits, the p-doped device obtained a clearly opened eye diagram. The results indicate that p-modulation doping could provide an improvement in the eye diagrams of high speed QD lasers.



Figure 4. Eye diagrams of the devices under a direct modulation rate of 10 Gb/s. (**a**) Un-doped device and (**b**) p-doped device.

3.4. Relative Intensity Noise Spectra

The optical feedback dynamics of the devices were investigated. In order to analyze the device operation above threshold, the bias current was maintained at 65 mA, which is around twice and three times higher than the threshold currents of the un-doped device and p-doped device, respectively.

Figure 5 shows the single-peak optical spectra of devices under different optical feedback intensities, respectively. As the optical feedback intensity increases from -60 to -12 dB, the spectrum wavelength of the un-doped device is maintained at 1215.66 nm, while that of the p-doped device redshifts from 1317.04 to 1317.07 nm. Because the optical feedback changes the mode gain, the laser field oscillation has to alter the cavity resonance frequency to maintain the steady-state laser intensity [21]. The bigger change in gain for p-doped QDs is accompanied by the larger redshift in the cavity resonance frequency and a smaller α -factor for the p-doped device. As the optical feedback intensity further increases to -9 dB, the un-doped device shows a drastic broadening of the laser linewidth, which signifies a

coherence collapse state. However, the spectra of the p-doped device are maintained as a typical F-P mode under -9 dB optical feedback intensity.



Figure 5. The optical spectra of devices with different optical feedback intensities. (**a**) Un-doped device and (**b**) p-doped device.

Finally, the relative intensity noise (RIN) spectrum of devices was also measured, as depicted in Figure 6. With the optical feedback intensity below -20 dB, the RIN spectrum of the un-doped device is stable, and the average intensity is around -135 dB/Hz. When the optical feedback intensity is increased to -15 dB, the intensity of the un-doped device increases in the low-frequency range. As the optical feedback intensity is further increased to -12 dB, the un-doped device shows a spectrum with a completely collapsed state. As a comparison, the RIN spectrum of the p-doped device maintains a low level of -135 dB/Hz under a large range of optical feedback intensity between -60 and -9 dB. The results demonstrate that the p-doped device has a much enhanced optical feedback resistance, which might be beyond -9 dB. In order to analyze the optical feedback sensitivity of devices, the critical feedback level for coherence collapse operation can be estimated [22]:

$$r_{\rm crit} = \frac{\gamma^2 \tau_{\rm L}^2}{16|C|^2} \frac{(1+\alpha^2)}{\alpha^4}$$
(2)

where C is the coupling coefficient, and τ_L is the photon cavity round-trip time. As aforementioned, compared with un-doped device, p-doped devices show a higher γ and a smaller α -factor, which result in a significant enhancement of the feedback resistance. This difference between the two devices can be explained by the QD carrier dynamics involving both capture and relaxation. The un-doped laser is more sensitive to optical feedback because of the stronger modal competition compared to the p-doped laser. Meanwhile, the excited state has higher degeneracy, leading to more radiative transitions, which will also reduce γ to the un-doped device [6,23].



Figure 6. The relative intensity noise (RIN) spectra of devices measured at 65 mA with different optical feedback intensities. (**a**) Un-doped device and (**b**) p-doped device.

4. Conclusions

In this paper, we have demonstrated 1.3 μ m p-modulation doped InGaAs/GaAs QD lasers with enhanced static and dynamic characteristics. With a cavity of 400 μ m long, the p-doped device shows a low threshold current of 17 mA and a maximum output power of over 23 mW. Dynamic characteristics of the p-doped device are also improved as a result of the p-doping. The device has a 7.8 GHz 3dB bandwidth and a clearly opened eye diagram under a directly modulation rate of 10 Gb/s. Moreover, with a higher damping rate and a smaller linewidth enhancement factor, the p-doped device has a much enhanced optical feedback resistance, which might be beyond –9 dB.

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