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Two-color quantum dot laser with tunable wavelength gap

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We report on two-color InAs/InP(100) quantum dot lasers with tunable wavelength gap. Two peaks of lasing emission were observed simultaneously, while the high energy peak undergoes continuous blueshift with the increase in the injection current, and the low energy peak is somewhat fixed. Sophisticated studies of the wavelength gap as a function of the laser power prove that the two-peak lasing and shifting is not caused by the effect of Rabi oscillation. Moreover, comparison of electroluminescence and lasing spectra under different injection currents reveal the blueshift of the high energy peak is most likely related to the state-filling effect. © *2009 American Institute of Physics*. [doi:10.1063/1.3278594]

Self-organized quantum dots (QDs) have been at the focus of interest for optoelectronic applications in the past decade.[1–4] Particularly, InAs QDs grown on InP are of great significance since high performance InAs/InP QD lasers covering the fiber optical telecommunication wavelength have been demonstrated by a few groups recently.[5–11] However, only few studies have been reported on the spectrum characteristics of the InAs/InP QD lasers. Special spectrum features from the QD lasers are naturally expected due to their unique quantum structure different from conventional quantum wells. Indeed, monolithic dual-wavelength QD lasers have been reported recently by Liu *et al.*,[8] where the peak splitting and shifting in the lasing spectra was observed. They tentatively explained this interesting spectrum characteristic by the model of Rabi oscillation. The key feature of Rabi oscillation is that the splitting frequency of two peaks linearly depends on the square root of the power density of the electromagnetic field. In this letter, we systematically investigated the spectrum characteristics of InAs/InP two-color QD lasers with tunable wavelength gap by varying the injection current and the operation temperature. The splitting frequency of the two lasing peaks as a function of the output power was carefully calibrated, which excluded that the two lasing peaks were resulted from the Rabi oscillation. Furthermore, electroluminescence (EL) spectra under high injection current were performed on a diode with one cavity facet intentionally damaged, which prevented the diode from lasing under large applied current. Blueshift of the EL peak was observed, where the EL peak and the high energy lasing peak exactly coincide in wavelength, indicating the state-filling effect is likely playing an important role in the blueshift of the high energy lasing peak.

The laser structure consisting of five-stacked InAs QD layers embedded in InGaAsP waveguide was grown on nominally (100) exact oriented n-type InP substrates by gas source molecular-beam epitaxy. Ridge waveguide QD lasers were fabricated with stripe width of 6 μm and length of 1.5 mm. The detailed material growth and device fabrication were described in Ref. 12. The chip with cleaved facet without coating was bonded on a heat sink whose temperature can be adjusted, and all the device tests were carried out under continuous-wave (CW) mode. The lasing spectra were measured by an optical spectrum analyzer with wavelength resolution of 0.01 nm, through a single mode fiber located close to the laser facet. The output power measurements were performed by Melles Griot optical power meter equipped with an integrating sphere Ge detector. Far-field pattern of the laser diode was measured as a single peak with symmetric shape, indicating that fundamental transverse-mode operation was obtained in the full range of injection current. A laser diode with one cavity facet intentionally damaged was fabricated for EL measurements under large injection current. The EL spectra were collected by a Fourier transform infrared spectrometer using InGaAs detector with detection wavelength up to 1.65 μm.

The lasing spectra of a QD laser under CW mode at a heat sink temperature of 20 °C are shown in Fig. 1(a), with injection current varied from 160 to 500 mA. Multimode lasing starts at a threshold current of 160 mA, with only one main peak centered at 1578 nm. The lasing spectra become slightly broadened as the injection current increased up to 200 mA, followed by a sudden appearance of a new peak centered at 1593 nm with current of 220 mA. During further increase in applied current, the low energy peak broadens slightly but with central wavelength almost fixed at 1593 nm. On the contrary, the high energy peak shifts continuously to shorter wavelength from 1579 to 1558 nm, corresponding to injection current of 210 and 500 mA, respectively. The dependence of intensity weighted central wavelength on the injection current is shown in Fig. 1(b). It is found that the blueshift of the high energy peak occurs drastically at the beginning but gradually saturated in the end, covering the wavelength window of about 21 nm. The above phenomenon is drastically different from the conventional two-state lasing observed in QD lasers,[13] where the wavelength of the peaks due to the ground-state-transition and the excited-state-transition are almost independent to the injection current, and the lasing from the excited-state-transition only occurs when the transitions of ground state

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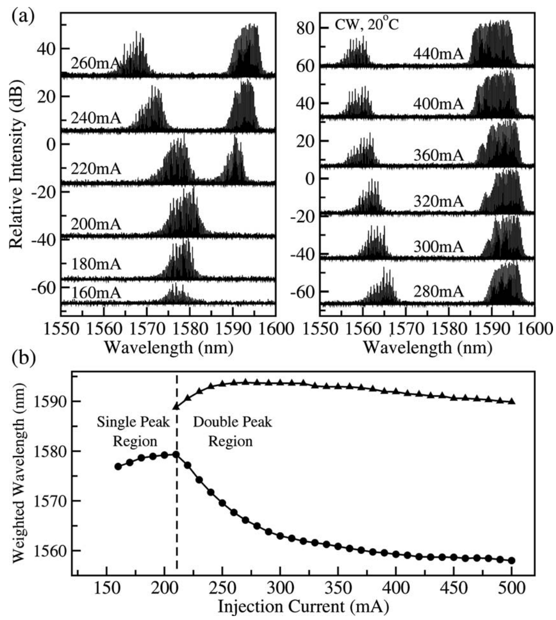

FIG. 1. (a) Lasing spectra of the QD laser with different injection currents in CW mode at 20 °C. (b) The current dependence of the intensity weighted central wavelength of the lasing peaks. The single peak and double peak region are divided by the dashed line.

saturated with the increase in injection current.

The reason for peak splitting and shifting in lasing spectra of InAs/InP QD lasers mentioned above is still unclear at present. One tentative explanation has been proposed by Liu *et al.*,[8] which is based on the model of Rabi oscillation. In this model, the single emission peak due to recombination of an exciton trapped by a InAs QD will split into double peak when the exciton state interacts with a resonant electromagnetic field strong enough.[14] The peak splitting in frequency is proportional to the square root of the power density of the electromagnetic field, as theoretically predicted and experimentally verified. Therefore, we calibrate carefully the peak splitting in frequency observed in the QD laser as a function of the square root of the output power. Note the power density in the laser cavity is proportional to the output power, which depends on the injection current as shown in Fig. 2(a). The splitting frequency, i.e., the frequency difference between the intensity weighted centers of the two peaks, versus the square root of the output power is shown in Fig. 2(b), which is obviously nonlinear. The splitting frequency increases mainly in the low output power region but saturates gradually with the increase in the output power.

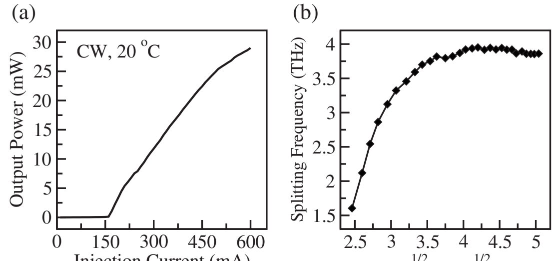

FIG. 2. (a) Output power vs injection current of the QD laser measured at 20 °C in CW mode. (b) The dependence of the splitting frequency on the square root of the output power.

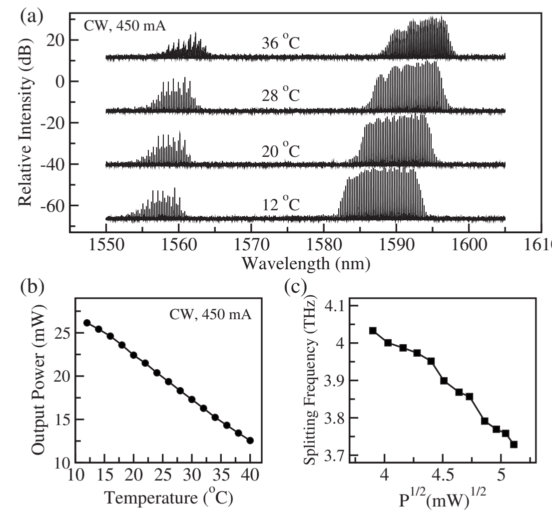

FIG. 3. The QD laser operates at different temperatures with injection current of 450 mA in CW mode. (a) The lasing spectra, and (b) the output power vs operation temperature. (c) The dependence of the splitting frequency on the square root of the output power.

The nonlinear dependence of the splitting frequency on the square root of the output power casts doubt on the explanation of double peak lasing and shifting in InAs/InP QD lasers by the Rabi oscillation model. In the following, we show that the splitting frequency may even decrease with the increase in output power of the QD laser diode, which qualitatively violate the model of Rabi oscillation. Temperature dependences of the lasing spectra as well as the output power are characterized on the laser diode operated at 450 mA. Redshift is observed for both peaks when the heat-sink temperature rises from 12 to 40 °C as shown in Fig. 3(a), while the output power decreases from 26 to 12.5 mW as shown in Fig. 3(b). It is surprising that the splitting frequency decreases monotonously from 4.03 to 3.71 THz with the increase in the square root of the output power from 3.9 to 5.1 $(mW)^{1/2}$, as shown in Fig. 3(c). Therefore, the peak splitting in lasing spectra of InAs/InP QD laser can hardly be explained by the model of Rabi oscillation.

The state-filling effect may be significant in the QD system due to the delta-function density of state in QDs and the limited dot density, commonly indicated by the blueshift of EL emission with the increase in injection current. In order to apply high injection current to a diode for EL measurements, we intentionally fabricated a diode (EL sample) with the same stripe length and width but an imperfect cleaved facet. Thus, the EL sample never lases and the injection current with same density can be, respectively, applied to the EL sample and the normal laser diode. The blueshift of EL spectra with increase in injection current is shown is Fig. 4, where the lasing spectra of a laser diode with the same dimensions as the EL sample and working under the same conditions are shown as well. For clarity, only high energy peaks of the lasing spectra are drawn and the low energy peaks are abbreviated as a vertical dashed line in the figure. Interestingly, the position of the high energy lasing peaks exactly coincide with that of the EL peaks under same injection currents, indicating the state-filling effect is likely to play an important role in the spectrum characteristics of InAs/InP QD lasers. In addition, a complicated assembly of state is formed by contributions from high-density QDs with

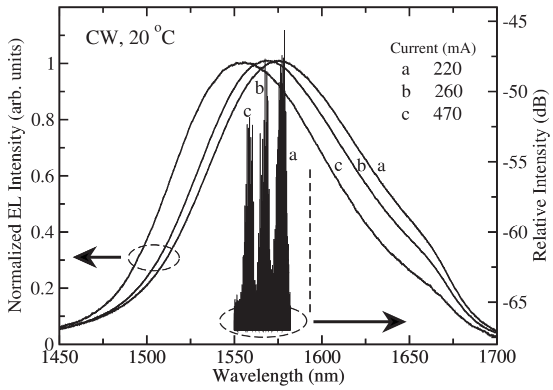

FIG. 4. The EL spectra of the intentionally fabricated sample working at 20 °C with different injection currents in CW mode. The lasing spectra of the QD laser with same dimensions and working conditions are shown as well, while the low energy peaks are abbreviated as the vertical dashed line.

large size distribution, leading to a very broad gain profile. Two-peak lasing might occur within the broad gain profile under specific conditions, which allow two lasing peaks coexist with different behavior determined by the mode or gain competition.

To summarize, we have demonstrated two-color InAs/InP QD lasers with the wavelength gap between two lasing peaks tunable by adjusting the injection current. During wavelength tuning, the low energy lasing peak is nearly kept at 1593 nm while the high energy one shifts gradually from 1579 to 1558 nm. The dependence of the splitting frequency on the square root of output power is found to violate the theoretical prediction by the model of Rabi oscillation. This model, therefore, is not suitable to explain the peak splitting and shifting observed in InAs/InP QD lasers. EL spectra measured from an intentionally fabricated sample undergo blueshift with the increase in the injection current, while the EL peak exactly coincides with the high energy lasing peak when the EL sample and the normal laser diode are under same operation current. This close correlation of the EL and lasing spectra under same injection currents suggests that the spectrum characteristics of InAs/InP QD lasers mentioned above are likely to be caused by the state-filling effect.

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