Low-temperature characteristics of two-color InAs/InP quantum dots laser

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We report on the lasing characteristics of a two-color InAs/InP quantum dots (QDs) laser at a low temperature. Two lasing peaks with a tunable gap are simultaneously observed. At a low temperature of 80 K, a tunable range greater than a 20-nm wavelength is demonstrated by varying the injection current from 30 to 500 mA. Under a special condition, we even observe three lasing peaks, which are in contrast to those observed at room temperature. The temperature coefficient of the lasing wavelength was obtained for the two colors in the 80−280 K temperature range, which is lower than that of the reference quantum well (QW) laser working in the same wavelength region.

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Self-organized quantum dot (QD) lasers have generated a huge amount of interest due to their δ-like quantum density of state and displayed unique optical and electrical properties that are different in character to those of the corresponding (QW) laser and bulk material laser[1]. In past years, good performances of QD lasers have been obtained in terms of a broad gain profile, low threshold current, high characteristic temperature, and high temperature wavelength stability[2−9]. The special features from the QD laser are naturally expected from their unique quantum structure providing extreme confinement for carriers, which results in multiple colors emitting simultaneously from a monolithic chip. Recently, at room temperature, a two-color emission from a monolithic chip of InAs/InP QD laser was reported as a result of the increase of an injection current[10,11]. The operation temperature was found to have an important effect on the performance of the two-color QD laser. At cryogenic temperatures, the QD lasers always display some special features different from those at room temperature. The obvious differences stem from the carriers' distribution in the non-uniform QD. At low temperatures, the carriers are always localized in the dots in which they are initially captured[12]. In the end, the laser performs some special characteristics as the injection current increases.

In this letter, we carefully investigated the two-color features of an InAs/InP QD laser from a monolithic chip at a low temperature. Two peaks of lasing emission were observed simultaneously: The high energy peak underwent a continuous blue-shift with the increase of applied current while the low energy peak was somewhat fixed. A tunable range of greater than a 20-nm wavelength was obtained by adjusting the injection current from 30 to 500 mA. However, in the current range from 330 to 370 mA, we even obtained three-color lasing peaks simultaneously, which are in contrast to those observed at room temperature. At the same time, under a fixed injection current of 300 mA, the wavelength coefficients of 0.22 and 0.16 nm/K for the two colors in the temperature range of 80−280 K were obtained, which is better than that of 0.548 nm/K of the reference quantum well laser working in the same wavelength range. At the same time, we demonstrated that the two peaks of lasing emission are not caused by the effect of the Rabi oscillation at a low temperature.

The samples of QD laser were grown on nominally (100) exact oriented n-type InP substrates by gas source molecular beam epitaxy using gallium and indium as sources of the III element. On the other hand, the V element sources were obtained by introducing AsH3 and/or PH3 in a high temperature, where the gases are thermally decomposed at 1 000 °C. The QD laser consisted of a five-stacked layer separated by a 40-nm-thick InGaAsP barrier (λg=1.18 μm) as the active regions, which was embedded in a 200-nm-thick InGaAsP layer (λg=1.18 μm) for separating the confinement. Each QD layer was formed at 485°C with the InAs growth rate of 0.1 mL/s, while the AsH3 pressure in the line was set to 630 Torr and the growth chamber pressure was measured as 1.5×10^{-5} Torr during the InAs QD growth. The bottom and top cladding layers were 600-nm n-InP buffer and 1.5-μm p-InP, followed by 200-nm p-InGaAs contact layer. The detailed growth conditions have been described in previous studies[5]. The 6-μm ridge waveguide QD lasers were fabricated with a cavity length of 1.5 mm, with both facets left uncoated. The chips were bonded with indium, epilayer side up, on a copper heatsink and then mounted on a cryostat whose temperature varied from 80 to 300 K. All tests were carried out under continuous-wave (CW) mode. The lasing spectra were collected by a Fourier transformed infrared spectrometer using an InSb detector with a resolution of 0.125 cm^{-1}.

Temperature has a great impact on carriers' distribution in QD, which leads the laser to exhibit a special lasing process. At room temperature, we simultaneously observed a two-color emission from a monolithic chip of the InAs/InP QD laser and demonstrated that the two peaks of the lasing emission with a tunable wavelength gap were not caused by the effect of the Rabi oscillation[11]. We further studied the lasing characteristics of the same QD laser at a low temperature. The lasing spectra as a function of injection current is shown in Fig. 1(a). At a temperature of 80 K, multimode lasing started at a threshold current of 30 mA, which corresponds to the current density of 333 A/cm^2. The lasing spectrum shows only one peak with a central wavelength of 1 538 nm. However, when the injection increases to 40 mA, a new peak with a central wavelength of 1 538 nm appears in the low-energy side. By further increasing the applied current, the high-energy peak undergoes a continuous blue-shift, while the low-energy peak is somewhat fixed. In the current range of 30 to 500 mA, the central wavelength of the high-energy peak shifts from 1 538 to 1 516.8 nm while the wavelength gaps between the two lasing peaks enlarge from 13 to 31 nm, as shown in Fig. 1(b).

The entire lasing processes are almost the same as those observed at room temperature. However, at a low temperature of 80 K, the low-energy lasing peak broadens at the injection current of 330 mA and splits into double peaks at the applied current of 350 mA. The whole lasing spectra almost display three lasing peaks simultaneously, which are remarked by P_1, P_2, and P_3, respectively, as shown in Fig. 2. As the injection current increased, the P_3 performs the same lasing process as P_1 and gradually shifts to the high-energy side before finally disappearing at a current of 380 mA. A comparison the lasing processes with those observed at room temperature indicates that the obvious differences are from the carriers' distributions. The carriers' captured processes are considered to be a random process in the QD laser. At a low temperature, the carriers are localized in the dots where they are first captured without carriers' transferring in different sizes of dots[7]. The broad gain due to the large non-uniformity of the QD is, therefore, spread out throughout the QD spectrum, and the lasing wavelength happens to the dots with similar size distribution in which they get enough initial gain; thus, multicolor emission becomes possible due to the non-uniform size distribution of QD[7,12,13]. However, when the applied current increased, the temperature in the active region is caused by heat increases due to the less uniform quantum efficiency (a fraction of input electric power is converted into heat in the active regions), which increases the loss in the active region. Therefore, the gain profile cannot offset the loss in the active region, and the lasing peak of P_3 (the third lasing peak) disappears at the 380 mA current. When the operation temperature is greater than 90 K, the lasing peak of P_3 never appears again by the increase of injection current.

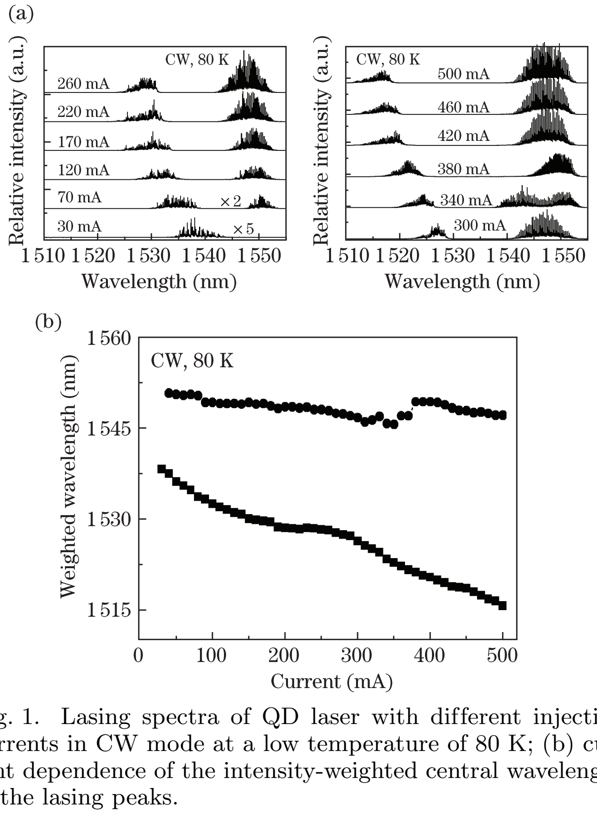

Fig. 1. Lasing spectra of QD laser with different injection currents in CW mode at a low temperature of 80 K; (b) current dependence of the intensity-weighted central wavelength of the lasing peaks.

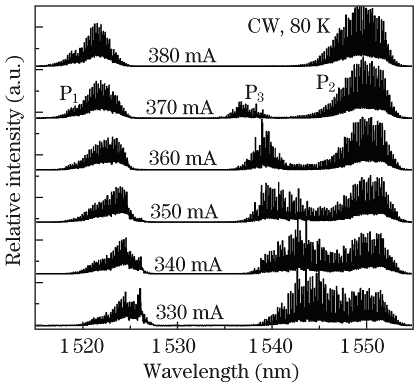

Fig. 2. Three-color emission wavelength of QD laser with applied current range from 330 to 380 mA in CW mode at a low temperature of 80 K.

In order to investigate the wavelength stability, we measured the two lasing peaks by varying the operation temperature in steps of 10 K. In the experiments, we fixed the injection current at 300 mA to exclude the wavelength shift caused by a current jump. When the temperature increased, both peaks shifted to the low energy side, as shown in Fig. 3(a). The same process was also observed in a quantum well laser (2.5 × 250 (μm)) working in the same wavelength region. As the temperature increases, the red-shift in the emitting wavelength is inevitable for semiconductor lasers due to the energy gap level shrinkage. In the 80−280 K temperature range, the shifts of two lasing peaks from the QD laser are 32 and 45 nm, respectively, while the wavelength of a quantum-well (QW) laser shifts quickly and reaches 95 nm. The temperature coefficients of 0.22 and 0.16 nm/K are obtained for low-energy and high-energy peaks respectively, which are better than that of 0.54 nm/K, as shown in Fig. 3(b). In the InAs/InP QD laser, the broad gain profile and state-filling effect play an important role

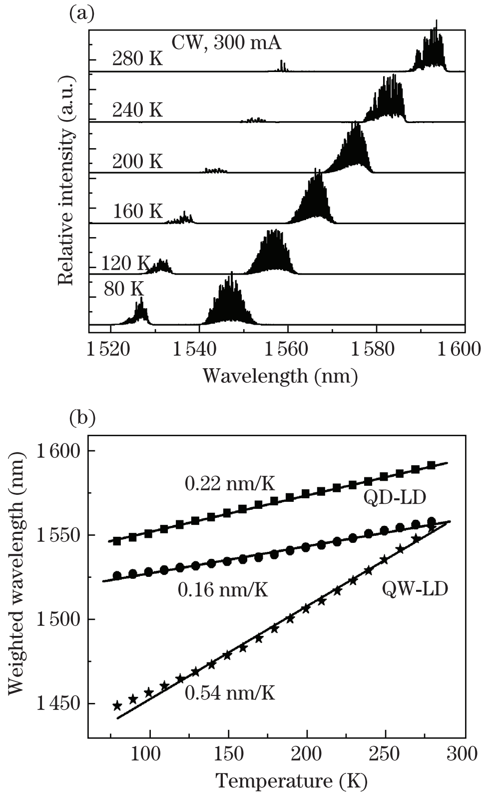

Fig. 3. QD laser operates at different temperatures with the injection current of 300 mA in CW mode. (a) Lasing spectra and (b) temperature coefficient of the lasing wavelength.

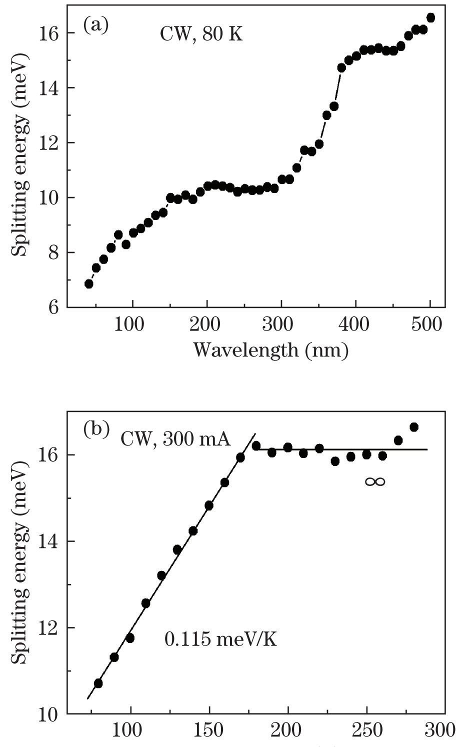

Fig. 4. Splitting energy with different injection currents in CW mode at a low temperature of 80 K; (b) splitting energy with different operation temperature in CW mode at a fixed current of 300 mA.

in wavelength stability, which partially compensates for the red-shift of the cavity mode while raising the operation temperature[4]. However, for the QW laser, mode-hoping to a longer wavelength is another main reason to reduce wavelength stability besides the energy gap level shrinkage when temperature increases.

The splitting energy between the two peaks is performed by the injection current and operation temperature. At a temperature of 80 K, the energy gap as a function of applied current is shown in Fig. 4(a). Three sections are found in the 40 to 500 mA current range and the splitting energy enlarges from 6.8 to 16.5 meV. Furthermore, we investigate the temperature dependence of splitting energy at a fixed current of 300 mA, as shown in Fig. 4(b). Two obvious sections are observed in the curve of temperature against the energy gap. In the temperature range from 80 to 180 K, the splitting energy gap increases with temperature at a coefficient of 0.115 meV/K. However, by further increasing the temperature, the splitting energy maintains a constant of 31 meV. The physical origin is still unclear at present. Recently, one tentative explanation proposed by Liu *et al.* was based on the model of the Rabi oscillation[10]. According to the model, the splitting peak in energy is proportional to the square root of the power density of the electromagnetic field in the active region of the QD laser[14]. When the operation temperature increases, the power density of the QD laser decreases due to the carrier's scarring effects[5]; in other words, the splitting energy should decrease with the increase of the temperature under a fixed current. However, in Fig. 4(b), we obtain an opposite relationship between the energy gap and operation temperature. The experiment further demonstrated that two peaks of emission from InAs/InP QD laser in the low-temperature region are not caused by the Rabi oscillation model demonstrated at room temperature.

The physical origin of special lasing processes from the QD laser greatly depends on the band structure of QD. The QD of the same material, but with different sizes, can provide different energy states due to the quantum confinement effect. In the self-assembly QD, the energy state can overlap, which means the excited state from the larger QD size overlaps with that of the ground state from a smaller QD, and then quasi-continuous band levels are formed. When the applied current increased, the continuous blue-shift of high energy lasing peak stemmed from the state filling effects, which have been demonstrated at a temperature of 20°C by a diode (EL sample) with the same stripe length and width, but with an imperfect cleaved facet[11]. However, the low-energy peaks remained fixed and do not appear in the maximum gain profile by increasing the injection current. The physical reason is not clear at present, so further studies are needed.

In conclusion, the characteristics of the two-color InAs/InP QD laser are carefully studied at a low temperature. At a temperature of 80 K, we observe three lasings simultaneously at a special injection current that are obviously different from those obtained at room temperature. We demonstrate the good wavelength stability of the QD laser, which is better that of a QW laser working in the same wavelength region. The splitting energy between high-energy peak and low-energy peak is investigated by increasing temperature, showing opposite relationships with temperature, which demonstrates that the two-color emission from the monolithic chip of the QD laser is not caused by the effect of the Rabi oscillation at a low temperature.

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