CHIN. PHYS. LETT. Vol. 28, No. 11 (2011) 114212

Multicolor InAs/InP(100) Quantum Dot Laser *

LI Shi-Guo(李世国)[1]**, GONG Qian(龚谦)[2], CAO Chun-Fang(曹春芳)[2], WANG Xin-Zhong(王新中)[1], WANG Rui-Chun[1](王瑞春), YUE Li(岳丽)[2], LIU Qing-Bo(柳庆博)[2], WANG Hai-Long(王海龙)[3]

[1]*Department of Electronic Communication and Technology, Shenzhen Institute of Information Technology, 1068 West Nigang road, Shenzhen 518029*

[2]*State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050*

[3]*College of Physics and Engineering, Qufu Normal University, Qufu 273165*

(Received 18 September 2011)

We report on a three-colour InAs/InP(100) quantum dot laser under continuous wave mode at an operation temperature of 20 °C. Three lasing peaks are observed simultaneously, the high-energy peak undergoes continuous blueshift, while the splitting energy gap between the low-energy peaks is somewhat fixed as the injection current increases. The maximum output power from one facet without coating is more than 34 mW with a slope efficiency of 102 mW/A just above the threshold current. Three peaks of differential efficiency of output power are observed, just corresponding to each peak in lasing spectra, respectively. At the same time, the far-field distribution shows only a single transverse mode over the full range of injection current.

PACS: 42.62.Fi, 78.67.Hc, 42.55.Px DOI:10.1088/0256-307X/28/11/114212

Quantum dot (QD) lasers have generated a huge amount of interest due to their δ-like quantum state density, which displays unique optical and electrical properties that are different in character to those of the corresponding quantum well (QW) laser and bulk material laser.[1] It has been reported that QD lasers exhibit good features, such as a high gain profile, a low threshold current density, high speed-modulation and high thermal stabilities.[2–7] In the past years, most studies have been carried out on the InAs/GaAs QD lasers (1.3 μm) and InAs/InP QD lasers (1.55 μm) and good performances of QD lasers have been obtained.[8–10] Especially, self mode-lock QD lasers with two-colour lasing peaks have been observed from a monolithic chip.[11–13] However, there has not been a careful study of the lasing process of multi lasing peaks from a monolithic chip. In this Letter, we systematically investigate the lasing characteristics of an InAs/InP(100) QD laser, which displays three-colour lasing peaks simultaneously under cw mode at an operating temperature of 20℃. The high energy peak undergoes continuous blue shift with the increase of injection current, while the low energy peaks are somewhat fixed. A single peak of the far-field pattern is observed in this laser diode in the full range of injection current. The output power from one cleaved facet laser without coating is more than 34 mW with a slope efficiency of 102 mW/A. The differential efficiency of output power shows two valleys in the range of the injection current, which just corresponds to the threshold current of the high energy lasing peaks, respectively.

The QD laser structure consisting of a five-stacked InAs layer was grown on nominally (100) exact oriented n-type InP substrate by gas source molecular beam epitaxy. Each QD InAs layer was separated by a 40-nm-thick InGaAsP barrier ($\lambda_g = 1.18$ μm) as the active regions, which was embedded in a 200-nm-thick InGaAsP layer ($\lambda_g = 1.18$ μm) for separate confinement. Each QD layer was formed by deposition 3.0 monolayer InAs at 485℃ with an InAs growth rate of 0.3 ML/s. The bottom and top cladding layers are 600 nm n-InP buffer and 1.5 μm p-InP followed by a 200 nm p-InGaAs contact layer. The detailed material growth conditions are described in Ref. [5]. Ridge waveguide QD lasers were fabricated with a stripe width of 8 μm and length of 1.5 mm. The chips with cleaved a facet without coating were bonded on a copper heat sink whose temperature could be adjusted and all device tests were carried out under cw mode. The lasing spectra were measured by an optical spectrum analyzer with a wavelength resolution of 0.01 nm, through a single mode fiber located close to the laser facet. The output power measurements were preformed by a Melles Griot optical power meter equipped with an integrating sphere Ge detector.

The light output power characteristics of the QD laser under cw mode at a heatsink temperature of 20℃ is shown in Fig. 1(a). The maximum output power from one facet is more than 34 mW with a slope efficiency of 102 mW/A, just slightly above the threshold current. The lasing spectrum of the QD laser diode at an injection current of $3.75I_{\rm th}$ is shown in the inset of Fig. 1(a), which simultaneously exhibits three las-

*Supported by the Natural Foundation of Guangdong Province under Grant Nos S2011040001330.

**Corresponding author. Email: lishiguo2002@163.com

© 2011 Chinese Physical Society and IOP Publishing Ltd

ing peaks with central wavelengths around 1565.9 nm, 1580.3 nm and 1591.2 nm, respectively. The differential output power efficiency was studied as a function of injection current, as shown in Fig. 1(b). With the increasing injection current, the efficiency curve shows three obvious peaks at the injection currents of 160 mA, 310 mA and 358 mA, respectively.

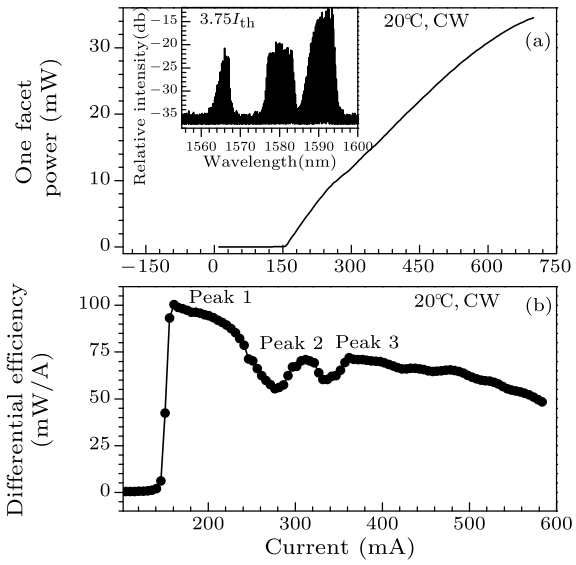


Fig. 1. (a) Output power versus injection current of the QD laser measured at 20°C under cw mode. (b) The powers' differential efficiency as a function of current. Inset: the three-color lasing spectrum at an injection current of $3.75I_{th}$.

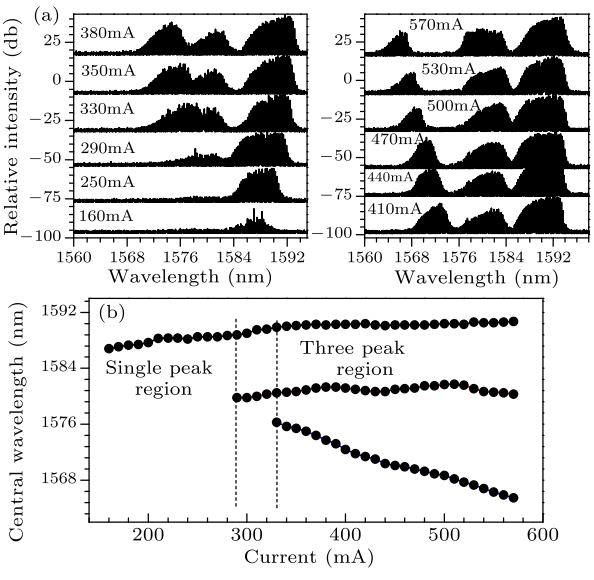


Fig. 2. (a) The lasing spectra of the QD laser with an injection current range from 160 to 570 mA. (b) The current dependence of the central wavelength of the lasing peaks. The single-peak, double-peak and triple-peak regions are divided by the dashed line.

To further study the lasing characteristics of the QD laser diode, we systematically measured the spectra by varying the injection current under cw mode at a heatsink temperature of 20℃. The lasing processes of the QD laser are shown in Fig. 2(a) by varying injection current from 160 to 570 mA. Multimode starts lasing at the injection current of 160 mA. There is only one main peak with a central wavelength of 1587.3 nm. With a further increase in the applied current, the lasing spectra gradually broaden and shift slightly to the lower energy side. When the injection current rises up to 290 mA, a new peak centered at 1580.1 nm starts lasing. By further increasing the applied current, another new peak with a central wavelength of 1576 nm appears at current of 350 mA, and then the high-energy peak undergoes continuous blueshift to a shorter wavelength, while both of the lower energy peaks are somewhat fixed, as shown in Fig. 2(b). A 11-nm wavelength shift is obtained by varying the applied current from 350 to 570 mA. Over the whole current range, the lasing spectra show a single color in the current range of 160–280 mA, double colors in 280–340 mA and three colors in 350–570 mA.

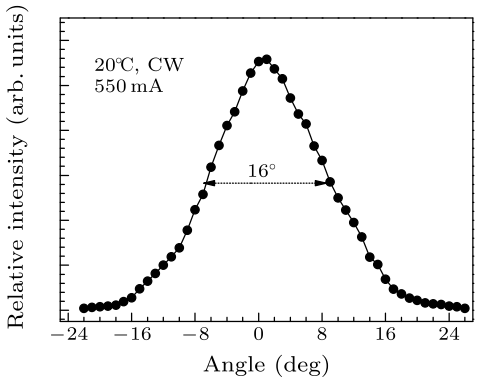


Fig. 3. Angle dependence of the far-field intensity distribution for the QD laser.

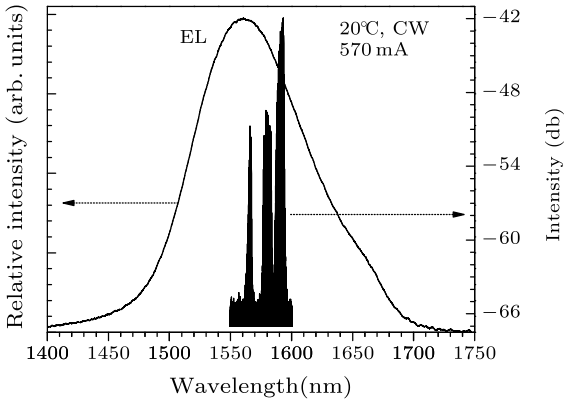


Fig. 4. The EL and lasing spectrum at a current of 570 mA under cw mode. The EL spectrum of the intentionally fabricated sample is working under the same conditions as the lasing spectrum.

Compared with the differential output power efficiency, the three lasing peaks coincide with the differential efficiency peaks. When the applied current reaches the threshold current, the number of photons

increases largely in the active regions. A lasing peak appears with a central wavelength of 1587.3 nm, which corresponds to the first peak shown in the powers' differential efficiency curve. It is noted that we took the one half of variation of power's differential efficiency as a threshold current of the lasing peak. By further increasing the applied current, carrier scattering caused by heat and the carriers' nonradiative recombination occurs in the active region of the QD laser, which leads to a decrease of powers' differential efficiency. However, when the injection current rises up to 290 mA, a new peak centered at 1580.1 nm starts lasing, which means that new photons with high energy add into the total power and then increase the differential efficiency. The physical origin is the same as the third peak in the powers' differential efficiency curve. The threshold currents coinciding with the three lasing peaks are 160, 290 and 350 mA, respectively, which happen to be the currents corresponding to one half of variation of the peaks in the power's differential efficiency curve.

Figure 3 shows the far-field intensity distribution of the QD laser diode as a function of the angle at the injection current of 550 mA. A single peak with a symmetrical shape is observed, indicating that fundamental transverse-mode operation was obtained in this QD laser diode. In order to apply a 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 an injection current with the same density can be, respectively, applied to the EL sample and the normal laser diode. The electroluminescence spectrum and lasing spectra at a current of 570 mA are shown in Fig. 4. The high-energy peak of the lasing spectrum happens to coincide with the EL peaks, which demonstrates that the continuous blueshift of the high energy lasing peak is caused by the quasi-continuous energy states due to the size nonuniformity of the QDs and state filling effects as the injection current increases. However, the low-energy peaks do not appear in the maximum gain profile. The mechanism for the special lasing characteristic of the QD laser is unclear at present. One explanation is related to the inhomogeneous broadened gain in the QD laser due to the size of QD uniformity, which can lead to the fact that the QD laser lases simultaneously in different spectral regions with an increasing current applied.[8] Another explanation is based on mode-lock, which leads to energy splitting owing to a large number of photons oscillating in the cavity. The multicolors are from the splitting energy. However, we have not completely explained the total performance of the multicolor quantum dot laser and further studies are therefore needed.

In summary, a three-colour InAs/InP(100) quantum dot laser with a tunable wavelength gap has been obtained by varying the injection current. The maximum output power from one facet is more than 34 mW, with a slope efficiency of 102 mW/A just above the threshold at an operating temperature of 20℃. Three peaks are found in the powers' differential efficiency curve, which are consistent with the peaks appearing in the lasing spectra during the increase in the applied current. The far-field distribution shows only a single mode in the full range of the injection current, indicating that the QD laser operates at the fundamental transverse-mode in this QD laser diode.

References

[1] Akiyama T, Hatori N, Nakata Y, Ebe H and Sugawara M 2002 *IEEE Electron. Lett.* **38** 1139

[2] Liu H C, Liew S L, Badcock T, Mowbray D J, Skolinick M S, Ray S K, Choi T L, Groom K M, Stevens B, Hasbullah F, Jin C Y, Hopkinson M and Hogg R A 2006 *Appl. Phys. Lett.* **89** 073113

[3] Lelarge F, Rousseau B, Dagens B, Poingt F, Pommereau F, and Accard A 2005 *IEEE Photon. Technol. Lett.* **17** 1369

[4] Anantathanasarn S, NÖtzel R, van veldhoven P J, van otten F W M, Barbarin Y, Servanton G, de vries T, Smalbrugge E, Geluk E J, Eijkemans T J, Bente E A J M, Oei Y S, Smit M K and Wolter J H 2006 *Appl. Phys. Lett.* **89** 073115

[5] Li S G, Gong Q, Lao Y F, He K, Li J, Zhang Y G, Feng S L and Wang H L 2008 *Appl. Phys. Lett.* **93** 111109

[6] Kim H D, Joeng W G, Lee J H, Yim J S, Lee D, Stevenson R, Dapkus P D, Jang J W and Pyun S H 2005 *Appl. Phys. Lett.* **87** 083110

[7] Alghoraibi I, Rohel T, Piron R, Bertru N, Paranthoen C, Elias G, Nakkar A, Folliot H, Le corre A and Loualiche S 2007 *Appl. Phys. Lett.* **91** 261105

[8] Lee C S, Guo W, Basu D and Bhattacharya P 2010 *Appl. Phys. Lett.* **96** 101107

[9] Deubert S, Debusmann R, Reithmaier J P and Forchel A 2005 *IEEE Electron. Lett.* **41** 1125

[10] Kotain J, van Veldhoven P J, de Vries T, Smalbrugge B, Bente E A J M, Smit M K and NÖtzel R 2009 *IEEE Electron. Lett.* **45** 1317

[11] Liu J R, Lu Z G, Raymond S, Poole P J, Barrios P J and Poitras D 2008 *Opt. Lett.* **33** 1702

[12] Li S G, Gong Q, Lao Y F, Yang H D, Gao S, Chen P, Zhang Y G, Fen S L G and Wang H L 2009 *Appl. Phys. Lett.* **95** 251111

[13] Charis M, Christos S, Hercules S, Spiros M, Igor K and Dimitris S 2010 *Appl. Phys. Lett.* **96** 211110

[14] Hadass D, Alizon R, Dery H, Mikhelashvili V, Eisenstein G, Schwertberger R, Somers A, Reithmaier J P, Forchel A, Calligaro M, Bansropun S and Krakowski M 2004 *Appl. Phys. Lett.* **85** 5505

[15] Kamada H, Gotoh H, Temmyo J, Takagahara T and Ando H 2001 *Phys. Rev. Lett.* **87** 246401