Low Threshold and 10kHz-Class Narrow Linewidth 1.55 μm-Band Quantum Dot Laser Diode on InP(311)B Substrate

A. Matsumoto,[1] R. Yabuki[2], S. Nakajima,[1] T. Umezawa[1], S. Heinsalu[2], Y. Matsushima,[2] K. Akahane[1], N. Yamamoto[1], and K. Utaka[2]
1 National Institute of Information and Communications Technology (NICT), Tokyo 184-8795, Japan
2 Faculty of Science and Engineering, Waseda University, Tokyo 169-8555, Japan
Author e-mail address: a-matsumoto@nict.go.jp

Abstract: We demonstrated low threshold current of 8.8 mA and 15.0 mA in pulsed and CW operation, and the extremely narrow linewidth of 12.2 kHz at room temperature in a fabricated 1.55 μm-band QD-DFB-LD.

1. Introduction

With the spread of smart devices such as smartphones and IoT products in recent years, as well as the advancement of various devices and technologies such as the progress of machine learning technology using a large amount of training data, the network traffic handled by short-range communication networks including 5G wireless and data centers shows a rapid increasing trend. Accordingly, high-capacity communication between data centers at distances exceeding 10 km is also becoming necessary. In short-distance communication, since compactness, low cost, and low power consumption are requirements for optical devices, the IMDD communication is used. However, even in DWDM and LWDM, there is a problem that the nonlinear effect of optical fibers, particularly the influence of four wave mixing, becomes significant at communication distances of about 2 km. Therefore, in recent years, a method called Coherent-Lite, which is a simplified coherent communication, has been proposed and studied. Even in this communication, while compactness, low cost, and low power consumption are required for the laser light source, it is also essential to narrow the laser linewidth to 100 kHz or less because the use of the modulation format of 16 QAM has been studied, and it should be required that it can be realized by the thermos-electric cooler (TEC) free operation in a wider temperature range [1]. On the other hand, optical components using quantum dot (QD) structure are promising as laser diodes (LDs) and optical amplifiers, and also for integration with Si photonics photonic integrated circuits and LSIs [2]. So far, we have experimentally demonstrated excellent temperature characteristics in QD-LDs [3] fabricated by using strain compensation technique and InP(311)B substrate [4].

In this work, we succeeded in improving the characteristics of the p-doped QD-DFB-LD, exhibiting a threshold current of 8.8 mA and 15.0 mA in the pulsed and CW condition at the temperature of 20 ºC, respectively, which was the lowest class reported previously as a 1.55 μm-band QD-DFB-LD as far as we know. Further, when the linewidth was measured, the value was very narrow, and a very good value of 12.2 kHz could be obtained at the current of 70 mA in 23 °C.

2. Results and Discussion

The fabricated p-doped QD-DFB-LD comprised n- and p-InAlAs cladding layers, 14 pairs of InGaAlAs embedding and InAs QD layers, and a p^+-InGaAs contact layer grown on an InP(311)B substrate. The thickness of InGaAlAs embedding layers was 20 nm in this time. As for p-type doping, beryllium (Be) atoms were doped in the active layer by the modulation delta-dope method with the concentration of 1 x 10^{18} cm^{-3}. Fig. 1 shows a Scanning Transmission Electron Microscopy (STEM) cross-sectional image of a QD wafer grown under almost the same condition as the QD-DFB-LD fabricated this time. As shown in the figure, clear QD structures were formed, and a typical size was approximately 3 nm in height and 30 nm ϕ in a plane direction. As for the fabrication of the sidewall grating structure, the grating pattern was formed on the wafer together with the mesa structure by inductively coupled plasma reactive ion etching (ICP-RIE) with using SiO_2 as a mask transferred by EB lithography. In this time, a λ/4 phase-shift structure was adopted in the grating, and the cavity width and length were 1.7 μm and 1000 μm, respectively. Both facets of the device were coated with HR and AR.

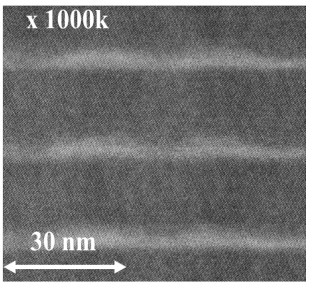

Fig. 1 STEM image of QD structure.

Fig. 2 indicates the temperature dependence of the optical output characteristics of QD Fabry-Perot LD with a typical ridge structure when the temperature was made varied from 15 to 150 °C in the condition of pulsed operation. The condition of pulse current was 1 μs width and 10 % duty ratio. As can be seen in the Fig. 1, lasing operation could be obtained up to a very high temperature of 150 °C. Fig. 3 is a graph showing the relationship between the threshold current and the temperature. From the result, the threshold current did not change substantially up to approximately 50 to 60 °C, indicating very high temperature stability.

Fig. 4 shows the lasing spectrum by CW operation when I_{op} = 50 mA at room temperature. The side mode suppression ratio (SMSR) was 50.1 dB, therefore sufficient single-mode characteristic could be obtained. Fig. 5 indicates the optical output power characteristics in pulsed and CW conditions, and voltage vs current characteristic. The condition of pulse current was the same as described above. The fabricated QD-DFB-LD indicated rather small threshold current of 8.8 mA and the corresponding threshold current density was 0.58 kA/cm^2 in the pulsed condition at the temperature of 20 ºC. In the CW operation, the threshold current of the QD-DFB-LD was 15.0 mA, corresponding threshold current density of 0.88 kA/cm^2, respectively. Threshold current and current density could be reduced by approximately 78.5 % than the previous our reported results [5] of the QD-DFB-LD. Furthermore, output power from QD-DFB-LD in pulsed condition exceeded 25 mW at 100 mA, and the saturation output power is expected to be even higher.

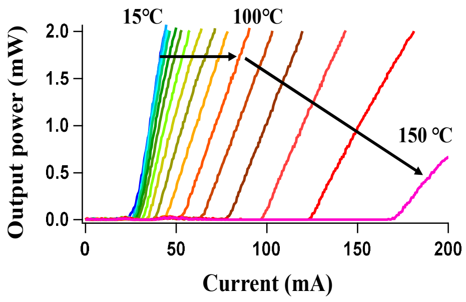

Fig. 2 Optical output characteristics in QD-FP-LD when the temperature was made varied.

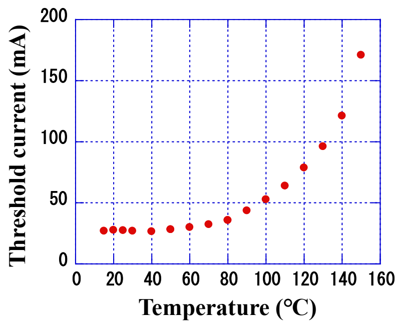

Fig. 3 The relationship between threshold current and temperature in QD-FP-LD.

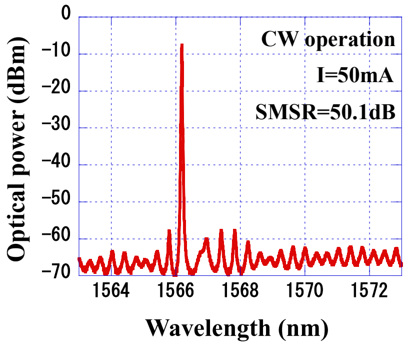

Fig. 4 Lasing spectrum of QD-DFB-LD.

Fig. 6 shows the temperature dependence of the lasing spectra in the case of I_{op} = 80 mA. The change of the peak wavelength due to the temperature change was estimated dλ/dT = 0.11 nm/°C, which was almost equivalent to that of a general DFB-LD. On the other hand, the temperature dependency of the gain peak wavelength was approximately 0.5 nm/°C according to previous our experimental results [6], and it is considered that the gain peak wavelength deviated from the Bragg wavelength as the temperature increased. Additionally, the relationship between the I-V characteristic at room temperature and the lasing peak wavelength at that time is shown in Fig. 7. As shown in Fig. 7, differential resistance was rather high, so considering the shift of the lasing wavelength with the increase of the current, it is presumed that the temperature increase in the active layer due to self-heating occurred in the fabricated QD-DFB-LD. Therefore, it is considered that the lowering of the maximum optical output power and the increase of the threshold current in the CW operation compared with the pulse are one of the factors.

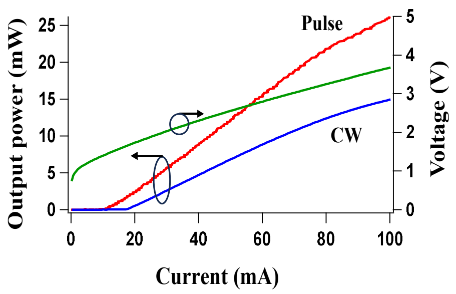

Fig. 5 I-L-V charactereistics of QD-DFB-LD in pulsed and CW conditions.

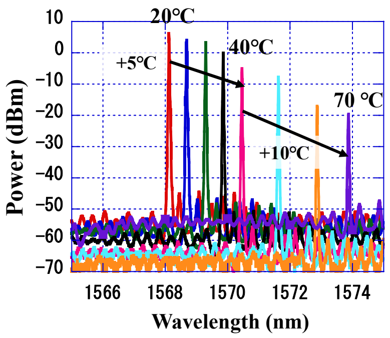

Fig. 6 Temperature dependence of lasing peak wavelength.

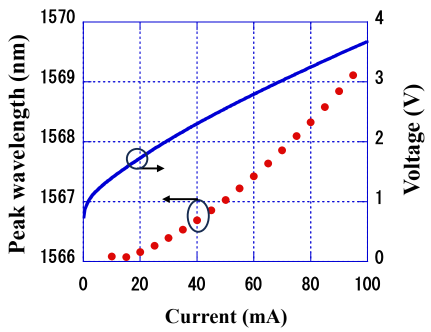

Fig. 7 I-V characteristic and the relation between lasing peak wavelength and current.

Then, the fabricated QD-DFB-LD chip was driven using a low-noise current source, and we performed linewidth evaluation using the delayed self-heterodyne method as shown in Fig.8. Fig. 9 shows the results of RF spectrum and Lorentz function fitting when I_{op} = 60 mA at room temperature. The obtained RF spectrum seemed to be relatively well fitted to the Lorentz function, and the linewidth of the laser estimated from this result was 14.0 kHz, which was rather narrow compared to conventional DFB-LD. One of the reasons for this was owing to the low α parameter. As previously reported, the value of α in our QD-LD was a value of 0.58 at room temperature, and it is considered that such a very small value of α resulted in a very narrow linewidth as shown in the Fig. 9. It is noted that the Lorentz function fitting to the whole line shape may suggest the uniformity of the QDs grown by our technique on InP(311)B compared to the Voigt function fitting for other cases [7]. In Fig. 10, the current dependence of the linewidth at each temperature is indicated. In this experiment, the RF spectra were measured about 50 times in a point, and the average value of the linewidth estimated from the RF spectra was shown in the graph. The linewidth was narrowest at 23 °C and I_{op} = 70 mA, and 12.2 kHz could be obtained. The linewidth becomes narrower as the output light power increases, i.e., as the injection current increases. As can be seen from this graph, the linewidth tends to gradually broaden at a current of 60 to 70 mA or more. As it is reported in the paper [7] that the value of the α parameter increased with temperature, the result shown in Fig. 10 is presumed to be caused by the fact that the value of the α parameter increased as the temperature in the active layer increased due to self-heating when the injection current increased as described above, while the gain saturation and the spatial hole burning might be partly responsible for it as well. The I-V characteristics can be improved by reviewing the device fabrication process, and it is expected that the optical output characteristics and the current dependence of the linewidth can be further improved.

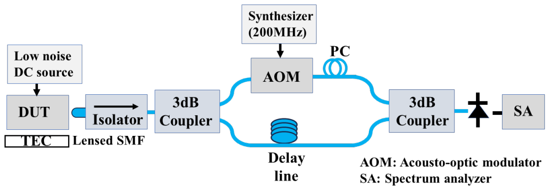

Fig. 8 Diagram of delayed self-heterodyne method.

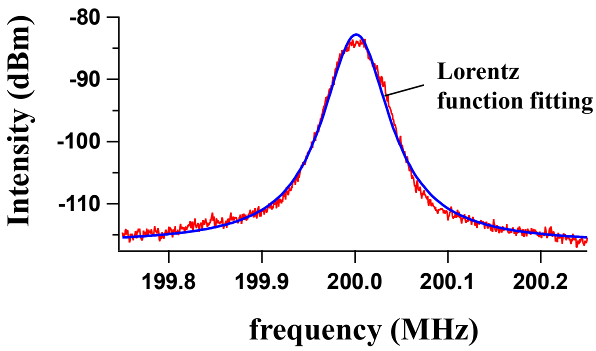

Fig. 9 RF spectrum measured by delayed self-heterodyne method and Lorentz fitting curve.

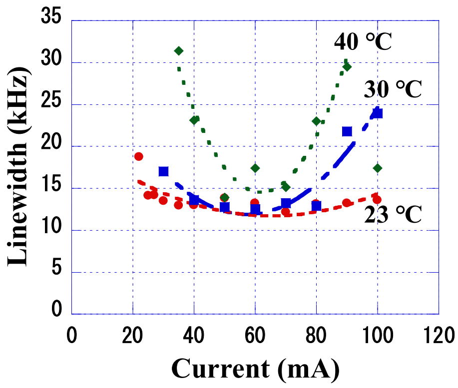

Fig. 10 the current dependence of the linewidth at each temperature.

3. Conclusion

In this paper, we succeeded in improving the characteristics of the p-doped QD-DFB-LD, exhibiting a threshold current of 8.8 mA and 15.0 mA in the pulsed and CW condition at the temperature of 20 ºC, respectively, which was the lowest class reported previously as a 1.55 μm-band QD-DFB-LD as far as we know. Furthermore, we demonstrated extremely narrow linewidth of 12.2 kHz at the current of 70 mA in 23°C, and furthermore, the linewidth is considerably narrow even at temperatures up to 40 ºC, and it is expected that the linewidth of 100 kHz necessary for the modulation format of 16 QAM can be satisfied over a wide temperature range.

5. Acknowledgement

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6. References

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