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ADP013012

TITLE: Power Conversion Efficiency in a Quantum Dot Based Diode Laser

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TITLE: Nanostructures: Physics and Technology International Symposium
[8th] Held in St. Petersburg, Russia on June 19-23, 2000 Proceedings

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Power conversion efficiency in a quantum dot based diode laser

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Abstract. Power conversion efficiency of diode lasers with the active region based on a quantum dot array is under investigation. The model is proposed which allows one to estimate analytically the optimal cavity length corresponding to the maximum power conversion efficiency at a given output power. The model is compared with the experimental results from high-power 0.94- μm diode lasers based on sub-monolayer quantum dots.

Introduction

Power conversion efficiency is one of the most important characteristics of any diode lasers. It depends on both the output power level and the cavity length. The same output power can be achieved from the diodes of various lengths whereas the conversion efficiencies are quite different owing to the differences in the threshold currents and the slope efficiencies. The output power at the point of peak conversion efficiency for the diode of a given length has been found in [1]. However, there can exist some cavity length(s) which corresponds to higher value of the conversion efficiency for the same power level. In the present work, optimization of the diode laser for high-efficient operation is considered as a search for the optimum cavity length, L_{opt} , which maximizes the power conversion efficiency for a given (designed) output power. We propose a simple analytical model which enables to determine these parameters for a diode laser with the active region based on array of semiconductor quantum dots (QDs). Also, their relationship with the internal characteristics of the diode lasers, i.e., series resistance, internal loss, transparency current, differential gain, *etc.* can be quantitatively predicted. Good agreement is observed when applying this model to a high-power 0.94- μm diode lasers based on sub-monolayer InAs/GaAs (QDs).

1. Conversion efficiency

Power conversion efficiency, η_C , is defined as the ratio of the output optical power from diode facets to the electrical input:

$$\eta_C(P, L) = \frac{P}{IV_0 + I^2 R_S}, \quad (1)$$

where $I = P/\eta + I_{\text{th}}$ is the drive current which is necessary to apply for achieving the design output power η and I_{th} are cavity length (L) dependent differential efficiency and threshold current, respectively; V_0 is the diode turn-on voltage; $R_S = \rho_S/WL$ is the series resistance of the diode with the width of W . In opposite to analysis developed in [1], our approach is based on matching the condition $\partial\eta_C(P, L)/\partial L|_{P=\text{const}} = 0$. The solution of this equation

determines the optimum diode length, L_{opt} , at which the conversion efficiency reaches its maximum, $\eta_{\text{C}}^{\text{max}}(P)$, for the given power, P . It can be shown that this is equivalent to expression:

$$V_0 C + 2R_S I C = -I^2 \frac{dR_S}{dL}, \quad (2)$$

where $C \equiv dI/dL |_{P=\text{const}}$. It is obvious that C parameter depends on both the power and the cavity length. In general case, this dependence is rather complex because it involves variation of both I_{th} and η with L . However, in the case of a diode laser based on an array of QDs, Eq. (2) can be significantly simplified giving a mathematical expressions for L_{opt} and $\eta_{\text{C}}^{\text{max}}(P)$ under analysis. The characteristic feature of a QD laser is the linear relationship between threshold current density, J_{th} , and modal gain, g :

$$g = \beta(J_{\text{th}} - J_0), \quad (3)$$

under condition that g does not exceed the saturated gain, g^{sat} . Here β is the differential gain (with respect to current density) and J_0 is current density at the transparency. Thus,

$$C = \frac{P\alpha_i}{\eta_0 r} + W \left(\frac{\alpha_i}{r} + J_0 \right), \quad (4)$$

where η_0 is the internal differential efficiency, α_i is the internal loss, $r = 1/2 \ln(1/R_1 R_2)$, $R_{1,2}$ is the facet power reflectivities. Substituting Eq. (4) into (2), the optimum cavity length of a QD diode laser, L_{opt} , and the corresponding maximum conversion efficiency $\eta_{\text{C}}^{\text{max}}(P)$ are finally given by:

$$L_{\text{opt}} = \frac{I_{\text{P}}^0}{C\sqrt{1+B^2}}, \quad \eta_{\text{C}}^{\text{max}}(P) = \frac{P}{V_0 I_{\text{P}}^0} \frac{B}{(1+\sqrt{1+B^2})^2}, \quad (5)$$

where $B = WV_0/\rho_S C$ and $I_{\text{P}}^0 = P/\eta_0 + Wr/\beta$ are length independent parameters. Substituting the experimental parameters of the laser structure, such as specific resistance, internal loss, etc one can design the cavity length and facet reflectivities by such manner to achieve the maximum conversion efficiency for the practically desired level of power output. On the other hand, Eq. (5) allowed one to optimize the laser structure for high-efficient operation by estimating the relative importance of different internal parameters. Applicability of the proposed optimization scheme is discusses below, where we consider high-power diode lasers based on sub-monolayer InAs/GaAs QDs.

2. Experiment

Sub-monolayer QDs are formed as a result of molecular beam epitaxial deposition of a short-period InAs/(Al)GaAs superlattice on a GaAs(100) surface with the InAs effective thickness of less than 1 monolayer (ML). High-power operation of 0.94- μm diode lasers with SML QDs has been recently reported [2]. Diode lasers discussed in this work have 100- μm -wide uncoated facets and were tested under CW excitation at 10°C. Figure 1(a) shows the experimental power conversion efficiency as a function of the power for two different cavity lengths. It is seen that $P = 1.9$ W corresponds to the peak conversion efficiency (50.5%) for $L = 1.76$ mm. On the other hand, there exist the other cavity lengths which result in higher conversion efficiency at $P = 1.9$ W. In particular, at $L = 1.04$ mm the power conversion efficiency of 58% is achieved at 1.9 W. This example shows the importance of the analysis above for optimization of efficiency characteristics. Assuming the transparency

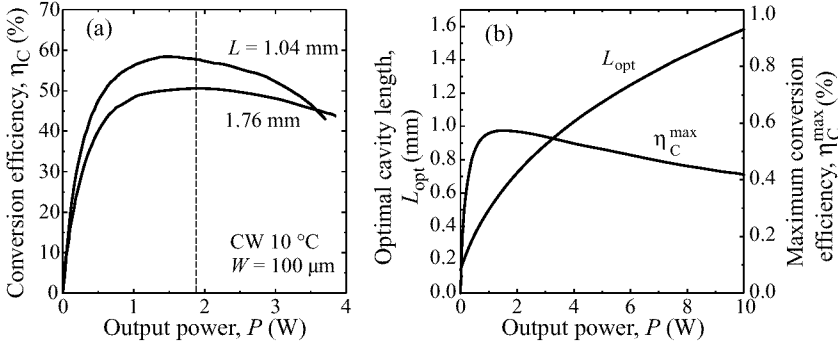


Fig. 1. Efficiency characteristics of 0.94- μm diode lasers based on sub-monolayer QDs. CW regime, 10°C. (a) Power conversion efficiency versus output power for two diode lengths; (b) Optimum cavity length and maximum conversion efficiency at 2 W calculated under assumptions $\beta = 0.06$ cm/A, $J_0 = 90$ A/cm², $\rho_s = 1.244 \times 10^{-4}$ Ω cm², $V_0 = 1.37$ V, $\alpha_i = 2.3$ cm⁻¹, $\eta_0 = 1.31$ W/A.

current density of $J_0 = 90$ A/cm² and the differential gain of $\beta = 0.06$ cm/A, Eq. (4) gives a good agreement with the experimental data in the range of $J_{\text{th}} < 500$ A/cm² ($L > 0.5$ mm). For the shorter cavities (higher J_{th}), the modal gain saturates at $g^{\text{sat}} = 21.5$ cm⁻¹. This is, to our best knowledge, is the highest saturated gain ever reported for QD lasers of any kind with single QD plane in the active region. Maximum conversion efficiency, η_C^{max} , and corresponding optimum cavity length, L_{opt} , calculated by is Eq. (5) are shown in Fig. 1(b) as functions of the optical power, P . Internal parameters are shown in the caption. It is seen that the optimum cavity length increases with P . The maximum conversion efficiency for the power range of 2–4 W, which was achieved in SML diode lasers with uncoated facets, corresponds to the optimum cavity length of about 1 mm. The experimental results (Fig. 1(a)) are in a good agreement with the calculation. The power conversion efficiency in excess of 55% is measured in a wide range of output power (1–2.5 W) in the 1.04-mm-long diode. The maximum conversion efficiency is 59% which is, to the best of our knowledge, is the record high value for any QD lasers. It is worth mentioning that it is only 7% lower the highest result achieved by well established QW laser technology [3, 4].

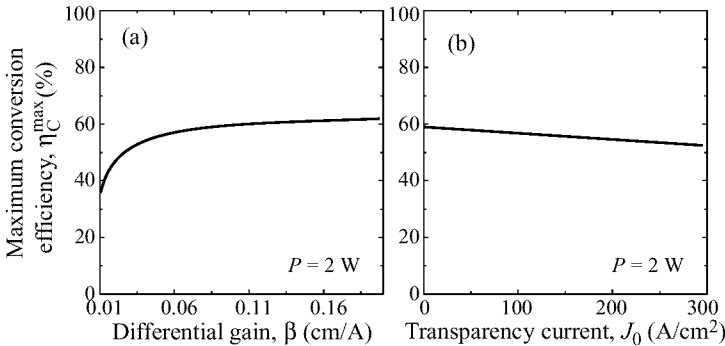


Fig. 2. Calculated dependence of the maximum power conversion efficiency at 2 W on the differential gain and the transparency current density. The other parameters are shown in the caption of Fig. 1.

As an example of relationship between internal laser parameters and efficiency characteristics, Fig. 2 shows the dependence of η_C^{\max} at 2 W on the differential gain, β , and the transparency current density, J_0 . Both these parameters are closely related to the QD active region design. Figure 2(a) demonstrates that η_C^{\max} steeply decreases if the differential gain becomes lower than $\beta \sim 0.05\text{--}0.06$ cm/A. Differential gain of a QD laser is mostly governed by inhomogeneous broadening of the ground state transition was estimated to be 25 meV. This corresponds to β of 0.06 cm/A, which is our experimental result. According to the data of Fig. 2(a) this differential gain still results in high efficiency. On the one hand, less uniform QD array (lower β) could not provide high conversion efficiency. On the other hand, maximum conversion efficiency is practically unchanged with β higher than ~ 0.09 cm/A. Thus, formation of more uniform QD array can hardly improve significantly the efficiency characteristic. According to Fig. 2(b), η_C^{\max} weakly depends on the transparency current density, which, in the turn, is linearly proportional to the surface density of QDs. This means that the QD density can be noticeably increased without a significant effect on the efficiency. On the other hand, formation of denser QD array is strongly desired to improve the saturation gain and decrease the internal loss.

3. Conclusions

In summary, the power conversion efficiency of QD diode lasers is studied. Analytical model proposed allows us to evaluate the optimum cavity length which maximizes the conversion efficiency at the given output power. The maximum conversion efficiency and the optimum cavity length were calculated as function of the power as well as internal parameters of the active region. The calculation results are in a good agreement with experimental efficiency data on high-power 0.94- μm diode lasers based on sub-monolayer quantum dots.

Acknowledgement

This work is supported by RFBR and BMBF.

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