980-nm optically pumped semiconductor disk laser

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The design, fabrication, and characteristics calculation of 980-nm optically pumped semiconductor disk laser are reported. The laser combines a vertical cavity semiconductor laser with a partically reflecting out coupler and an external cavity for mode control. Pumped by 808-nm diode laser, the disk laser directly generates a linearly polarized, circularly symmetric, diffraction-limited beam with watt-level power. Calculation shows the laser with active region of InGaAs/GaAsP/AlGaAs system can operate at near 500-mW in a single transverse mode.

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The output power of single mode vertical-cavity surface-emitting laser (VCSEL) is limited to some milli-watts. To further increase the output power the active area has to be enlarged which leads to disadvantages like multimode behavior as well as problems with electrical pumping. To avoid multimode behavior an external cavity can be used instead of the top Bragg mirror, as it is demonstrated in the Novalux extended cavity surface emitting laser (NECSEL). However, homogeneous electrical pumping is still a challenge limiting the fundamental-mode output power of such a device to below 1 W[1,2]. To get around this, optical pumping can be applied, leading to the so called vertical external cavity surface emitting laser (VECSEL), optically pumped semiconductor laser (OPSL) or semiconductor thin-disk laser. However, the absorption in the multi-quantum wells (QWs) forming the active region of usual semiconductor disk-lasers is very low. Therefore, Mooradian *et al.* used barriers surrounding QW as absorption layers[3], and thus decoupled the pump radiation absorption from the QW absorption. This leads to relatively low spectral requirements for the pump diodes, because their wavelength only has to be shorter than the corresponding barrier material bandgap. Since the difference in the bandgaps of the QWs and the adjacent layers need to be sufficiently large, the minimal distance of pump wavelength to lasing wavelength is rather high, and sets a lower limit for the quantum defect of typically 20%.

The principle of a semiconductor disk laser is depicted in Fig. 1, with the details of the semiconductor wafer structure given in Fig. 2. In the simplest case, neglecting the pump source, it comprises two components only: an active mirror and a separate external spherical mirror with radius of curvature R_c. The semiconductor active mirror is composed of a highly reflective distributed Bragg mirror (DBR) followed by a stack of QW layers separated by spacer layers. A window layer on top of the chip prevents nonradiative surface recombination and surface oxidation. For optimal heat removal, the active mirror is soldered directly with its Bragg side onto a heat sink.

The OPS-VECSEL laser cavity in Fig. 1 consists of a planar on-chip mirror and an external spherical mirror with radius of curvature R_c. For the cavity length of L_c, the beam diameters ω_1 on the planar chip and ω_2 on the output spherical mirror are given by

$$\omega_1^2 = \frac{4\lambda L_c}{\pi}\sqrt{\frac{(R_c - L_c)}{L_c}}, \quad (1)$$

$$\omega_2^2 = \frac{4\lambda L_c}{\pi}\sqrt{\frac{L_c}{(R_c - L_c)}}). \quad (2)$$

In our experiments, the mode size on the chip is about 110 μm for the cavity length of $L_c = 20$ mm and mirror radius of curvature $R_c = 25$ mm. The same mode

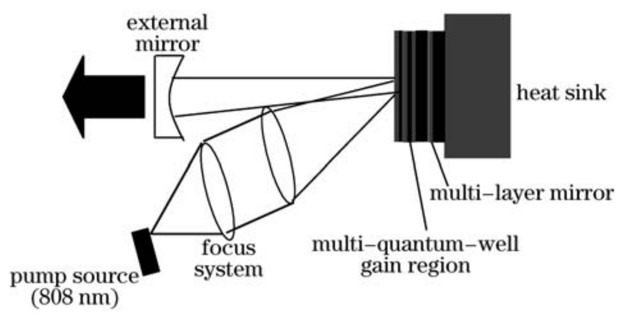

Fig. 1. Schematic diagram of semiconductor disk laser.

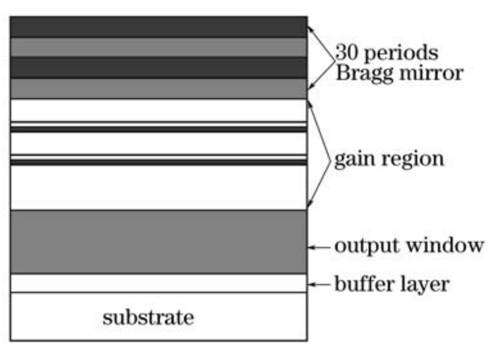

Fig. 2. Schematic structure of the wafer.

spot size can be achieved with an even more compact 5-mm-long cavity. The large (> 100 μm) mode spot size defines the required pump spot size, and it allows large area for heat extraction, lowers surface laser-light intensity, and ease transverse alignment tolerances of the laser cavity.

The theoretical predictions are made on the basis of the semi-empirical model introduced by Kuznetzov *et al.*[3]. We use the phenomenological logarithmic dependence of quantum well gain g on the carrier density N for the InGaAs/GaAsP/AlGaAs quantum well gain region in our device structure

$$g = g_0 \ln(N/N_0), \qquad (3)$$

where g_0 is the material gain parameter, and N_0 is the transparency carrier density. The output power of the laser is described as

$$P_{\text{las}} = (P_{\text{p}} - P_{\text{th}})\eta_{\text{diff}}, \qquad (4)$$

P_{p} is the pump power, P_{th} is the threshold pump power, and the differential efficiency η_{diff} is expressed as

$$\eta_{\text{diff}} = \eta_{\text{out}}\eta_{\text{quant}}\eta_{\text{abs}}, \qquad (5)$$

η_{abs} is the pump absorption efficiency, η_{out} is the output efficiency given by

$$\eta_{\text{out}} = \frac{\ln(R_{\text{ext}})}{\ln(R_{\text{bot}}R_{\text{ext}}T_{\text{loss}})}, \qquad (6)$$

R_{ext} is the laser output mirror reflectivity. η_{quant} is the quantum-defect efficiency expressed as

$$\eta_{\text{quant}} = \lambda_{\text{pump}}/\lambda_{\text{laser}}, \qquad (7)$$

where λ_{pump} is pump wavelength, and λ_{laser} is laser wavelength.

For further considering the thermal effect, we describe the output power P_{out} of the device as follows

$$P_{\text{out}} = (P_{\text{las}} - P_{\text{th}}) \times \left(1 - \frac{\Delta T}{T_{\text{off}}}\right). \qquad (8)$$

Temperature rise ΔT is given as

$$\Delta T = R_{\text{th}}(P_{\text{p}} - P_{\text{out}}). \qquad (9)$$

T_{off} is the temperature coefficient, R_{th} is the thermal resistance, which can be described as

$$R_{\text{th}} = (2\sigma D)^{-1}, \qquad (10)$$

where D is the pump spot diameter, and σ is the thermal conductivity.

Using the theoretical model presented above and InGaAs/GaAs quantum well material parameters based on reliable literature data[3,4], we calculated the performance of the optically pumped VECSEL device at 980-nm wavelength.

Figure 3 shows the calculated output power as a function of the number of InGaAs/GaAs QWs for different external mirror reflectivities (R_2). From Fig. 3, in small number ($n < 5$) of wells region, the output power increases very rapidly with the increasing of the number of wells, while for large number of wells ($n > 8$), the output power increases slowly. So there is an optimum number of quantum wells for the maximum output power. The output power is maximized for the well numbers between 5 and 8 from Fig. 3.

The external mirror reflectivity is also an important factor for the output power. To further optimize the structure, a change in R_{ext} should be performed. Figure 4 shows the dependence of output power on R_{ext} with pump power of 1500 mW and 8 quantum wells. So for the $R_{\text{ext}} = 98\%$, the output power P_{out} is up to the maximum output power about 600 mW.

Figure 5 shows the calculated output power as a function of the number of InGaAs/GaAs QWs for different pumped spot diameter. From Fig. 5, assuming pump power of 4 W, the output power increases when the pumped spot diameter is decreased.

Considering the thermal effect, Fig. 6 shows the calculated output power as a function of the input power for different pumping spot diameters. From Fig. 6, the heat

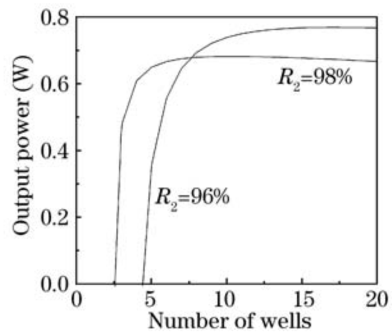

Fig. 3. Output power versus QW number.

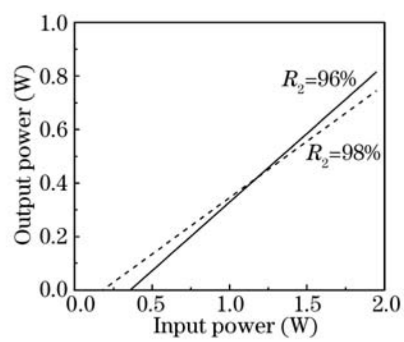

Fig. 4. Output power versus input power.

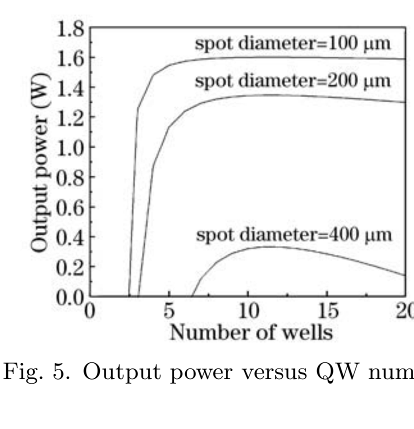

Fig. 5. Output power versus QW number.

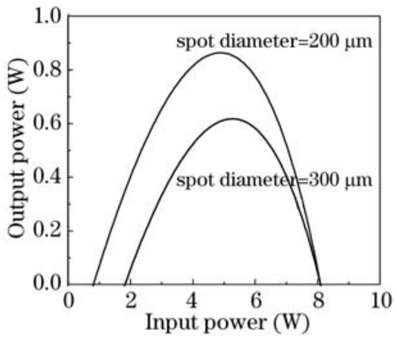

Fig. 6. Output power versus input power.

will result in the heat roll in the output characteristic.

In conclusion, we propose the design and numerical simulation of 980 nm high power optically pumped VECSELS, the device design realizes the integration of diode-pumped lasers with VCSEL structure, and combines the advantages of both. Using the laser and material parameters we calculate the output power theoretically for the number of quantum wells and different external mirror reflectivities. From the calculation results, an optimum number of quantum wells is obtained for the maximum output power. Considering the thermal effect and employing the optimum number of QW and external mirror reflectivity, the output power characteristics of the device at 980 nm is investigated theoretically.

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