High-Efficiency and High-Power Vertical-Cavity Surface-Emitting Laser Designed for Cryogenic Applications

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***Abstract*— We report the first vertical-cavity surface-emitting laser (VCSEL) that has been optimized for cryogenic applications near 77 K, with superior characteristics that include a high-output power (P_{out} = 22 mW at I = 25 mA), high power conversion efficiency (η_d = 32%), low threshold voltage (V_{th} = 1.75 V) and current (I_{th} = 1.7 mA), and low power dissipation (9 mW at P_{out} = 2.0 mW) for a 20-μm-diameter device.**

THE DEVELOPMENT of vertical-cavity surface-emitting lasers (VCSEL's) has made great strides in recent years, having achieved excellent room-temperature operating characteristics, including a very low threshold current density (400 A/cm^2) [1], [2] and low threshold voltage (1.6 V) [3], a low series resistance (<20 Ω) [4], thermally stable electrical characteristics [4], and a high-power conversion efficiency (21%) [5]. However, the room-temperature operation of VCSEL's is generally limited by its relatively small slope efficiency ($\eta_s < 35\%$) and low output power ($P_{\text{out}} < 10$ mW for a 20-μm-diameter device). It has been observed (Fig. 1) that the slope efficiency and the output power of proton-implant-isolated AlGaAs–GaAs VCSEL's improve dramatically as the temperature is decreased, with η_s approaching 100% at 77 K, and $P_{\text{out}} > 20$ mW. This suggests that VCSEL's with superior performance can be achieved at cryogenic temperatures, including a higher wall-plug efficiency and higher output power, and very low power dissipation. Such a VCSEL would be well suited as a low-power source for a high-speed optical data link operating at cryogenic temperatures, which could be used, for example, as a read-out link for a focal-plane array in satellite and space imaging applications [6] in which power dissipation must be kept to a minimum.

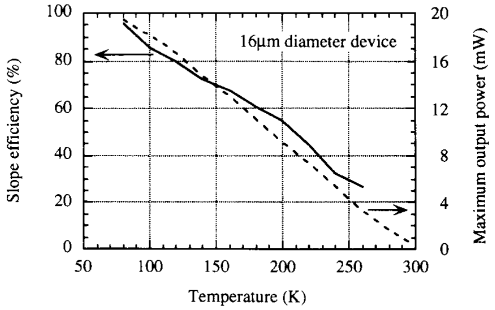

Fig. 1. The temperature dependence of the differential slope efficiency and the maximum-output optical power of a VCSEL with a 16-μm active area diameter.

To achieve low power consumption (P_d) and high power conversion efficiency (η_{eff}), the VCSEL must have a very low threshold current (I_{th}) and a low operating voltage (V), in addition to a high slope efficiency (η_s). The former is achieved by designing the VCSEL so that optimal alignment of its lasing mode and gain peak occurs at the desired low temperature [7]. The operating voltages are reduced by lowering the barrier height at the VCSEL mirror's hetero-interfaces, which become more prohibitive to carrier transport as the temperature is reduced, thereby resulting in a large increase in V_{th} [4]. Various grading and doping techniques have been successfully applied to reduce these barrier heights and thus produce low and thermally stable operating voltages. Using parabolic grading of the mirror heterointerfaces [8], a minimum barrier height has been achieved even at a low doping level ($5 \times 10^{17}/\text{cm}^3$). In this paper we report the first VCSEL that has been optimized for operation at 77 K, with characteristics that are superior to those of similar VCSEL's optimized for 300-K operation. Very high output power ($P_{\text{out}} = 22$ mW at $I = 25$ mA), high power conversion efficiency ($\eta_{\text{eff}} = 32\%$), high slope efficiency ($\eta_s > 75\%, \eta_s \approx 100\%$ for some devices), low threshold voltage ($V_{\text{th}} = 1.75$ V) and current ($I_{\text{th}} = 1.7$ mA), low threshold current density (540 A/cm^2), and low power dissipation ($P_d < 9$ mW at $P_{\text{out}} = 2.0$ mW) have been achieved by a 20-μm-diameter device.

The VCSEL consists of a single-wavelength-thick optical cavity, which contains a four-quantum-well active layer sandwiched between two distributed Bragg reflectors (DBR's) with parabolically graded heterointerfaces grown by metalorganic chemical vapor deposition. The upper and lower DBR mirrors contain 25 pairs and 38.5 pairs of $\text{Al}_{0.95}\text{Ga}_{0.05}\text{As}$ and $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ quarter-wave layers, respectively, and the doping concentration is graded from $1 \times 10^{18}/\text{cm}^3$ near the surface to $5 \times 10^{17}/\text{cm}^3$ near the active layer. The cavity

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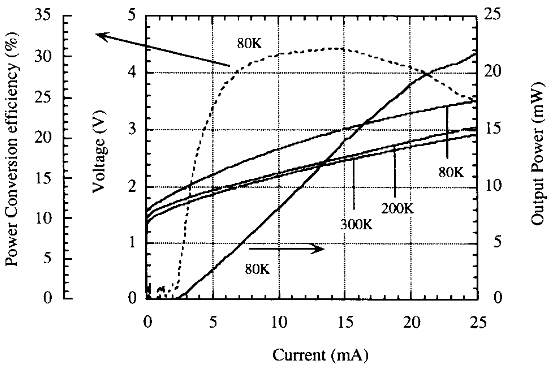

Fig. 2. The I-V characteristics of a 20-μm-diameter VCSEL at three different temperatures, and its L-I characteristic and power conversion efficiency at 80 K are shown.

mode (810 nm) is intentionally de-tuned from the gain peak (850 nm) at room temperature, and is aligned to the latter at 100 K, where the lowest lasing threshold occurs [7]. Fig. 2 shows the current-voltage (I–V) characteristics of a 20-μm-diameter device at three different temperatures (80, 200, and 300 K), and its light-current characteristic at 80 K. The operating voltage at a fixed current level of 25 mA varies by only 0.7 V from 300 K to 80 K, which indicates that a very low barrier height has been achieved at the DBR heterointerfaces by parabolic grading. At 80 K, the threshold current and voltage are 2.2 mA and 1.8 V, respectively, and the slope efficiency is 75% ($\eta_s \approx 100\%$ for some devices), and the maximum output power is 22 mW at $I = 25$ mA. The light-current characteristic is linear up to a current level of almost $10 \times I_{\mathrm{th}}$ (22 mA), and the slope efficiency is high ($\approx$75%). The power conversion efficiency is also shown in Fig. 2, which has a maximum of 32%, and stays at a high level ($\eta_{\mathrm{eff}} > 28\%$) over a broad current range (from 7 mA to 22 mA).

Fig. 3 shows the temperature dependence of V_{th} and I_{th}. The voltages are low (<2.4 V) and, except for the temperature dependence of the bandgap, are relatively stable (0.6 V change) over the entire temperature range from 80–300 K, which is essential for low power dissipation. The minimum I_{th} of 1.7 mA ($J_{\mathrm{th}} = 540$ A/cm^2) is achieved at 100 K in accordance with our design. Fig. 4 shows the power dissipation of the VCSEL as a function of temperature at several constant optical output power levels, which also represents $\eta_{\mathrm{eff}} = P_{\mathrm{out}}/P_d$ as a function of temperature and bias. At the optimum temperature (100 K), the power dissipation is 3 mW at threshold, 6 mW for $P_{\mathrm{out}} = 1$ mW, 9 mW for $P_{\mathrm{out}} = 2.0$ mW, and 32 mW for $P_{\mathrm{out}} = 10$ mW (with $\eta_{\mathrm{eff}} \approx 30\%$). The low power dissipation at low temperatures is a consequence of the low operating voltages and currents that have been achieved by design, and the high slope efficiency.

In conclusion, we have reported the first VCSEL's that were intentionally optimized for 77 K operation to take advantage of the high efficiency and high output power that can be achieved at low temperatures. Low threshold current density, very low power dissipation, high output power, and a high power conversion efficiency have all been achieved in a single device, and exceed the characteristics of similar VCSEL's at 300 K. With a value of η_s approaching 100%, a power conversion efficiency of greater than 50% is possible. These results confirm that the VCSEL is a suitable source for cryogenic optical link applications.

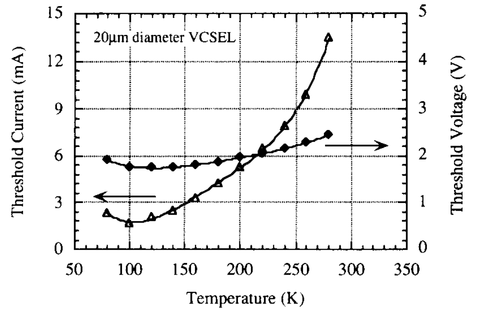

Fig. 3. Threshold current and voltage as a function of temperature, indicating small variation in V_{th} and optimum operation at 100 K.

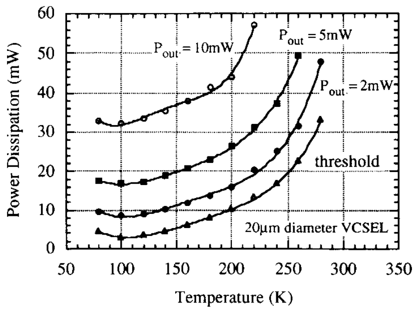

Fig. 4. Power dissipation of the VCSEL as a function of temperature at several constant optical output power levels.

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