Lasing characteristics of lasers with a vertical cavity based on In$_{0.2}$Ga$_{0.8}$As quantum wells


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Semiconductor lasers with a vertical cavity with a high external quantum efficiency and high radiation power have been developed and constructed. Powers up to 10 W at $T=300$ K and 20 W at $T=250$ K have been obtained for 500 $\mu$m aperture lasers operating in the pulsed regime. © 1999 American Institute of Physics.

In the last few years, progress in the development of semiconductor lasers has largely been determined by the development and construction of lasers with a vertical cavity (LVC). The record results for the threshold current, current-modulation frequency, and radiation divergence obtained for LVCs$^{1–5}$ substantially expand our understanding of the possibilities of semiconductor emitters and stimulate further investigations in this field. In the present letter we report the results of an investigation of the lasing characteristics of LVCs, whose structure has been optimized in order to achieve high external quantum efficiency and high radiation powers.

The initial laser structures were grown by molecular-beam epitaxy on $n^+$ (001) GaAs substrates. The laser structures contain undoped active regions of width $l$, which include three 8-nm In$_{0.2}$Ga$_{0.8}$As quantum wells and mirror regions with $p$- and $n$-type doping, forming a Fabry–Perot interferometer and consisting of multiply repeated GaAs and Al$_{0.9}$Ga$_{0.1}$As $\lambda$/4 layers (20 and 22.5 periods for the $p$ and $n$ mirrors, respectively). Carrier injection into the action region is done through the $p$ and $n$ mirrors. The GaAs and Al$_{0.9}$Ga$_{0.1}$As layers of the mirrors were doped to $1 \times 10^{18}$ cm$^{-3}$. To decrease the ohmic resistance of the mirror regions, the GaAs–Al$_{0.9}$Ga$_{0.1}$As interfaces contain 15-nm inserts with an Al composition gradient and high degree of doping (Be or Si: $5 \times 10^{18}$ cm$^{-3}$). The top $p$ mirror is terminated with an additional 47-nm heavily doped (Be: $1 \times 10^{19}$ cm$^{-3}$) GaAs layer, which functions as the contact region and ensures phase matching of the light reflected from the Ti (2 nm)/Au (120 nm) metallic coating and the semiconductor heteroboundaries. The layout of the LVC is displayed in Fig. 1a. The aperture (A) of the LVC is determined by the inner diameter of a Al$_2$O$_3$ ring, obtained by selective oxidation of the AlAs layers.$^6$ For this purpose, a 66-nm AlAs layer, located near the active region, is provided. The parameter $A$ was varied over a wide range from 2 to 1000 $\mu$m. The radiation of the LVC is extracted through a GaAs substrate with an antireflection coating.

Figure 1b shows the reflection ($R$) spectra of the laser structure, the electroluminescence spectrum ($E$), and the emission spectrum ($G$) of the LVC. The measured reflection spectrum (thick line) agrees well with the calculated spectrum (fine line) and contains a resonance of the Fabry–Perot interferometer near 965 nm, whose position is the same as that of the maximum of the electroluminescence spectrum. The lasing wavelength of the LVC corresponds to the position of the resonance of the interferometer.

The high external differential quantum efficiency $\eta_e$ of

![Diagram of a vertical-cavity laser](image-url)
the LVC which we developed results from the high internal quantum efficiency \(\eta_i > 0.9\) and the optimal ratio of the reflection coefficients of the mirrors: the top mirror is characterized by a very high value of the reflection coefficient \(R_t\), close to 1, and the bottom (exit) window is characterized by a relatively low coefficient \(R_b \approx 0.99\).

When \(R_t\) is close to 1 and the inequality \((1-R_t) \ll (1-R_b)\) is satisfied, the parameter \(\eta_e\) of the LVC is given by the expression

\[
\eta_e = \eta_i (1-R_b)(\alpha L + 1-R_b)^{-1},
\]

where \(\alpha L\) describes the optical losses in the cavity, \(\alpha\) is the absorption coefficient, and \(L\) is the cavity length. In accordance with Eq. (1), for \(\eta_i\) close to 1 and \(R_b = 0.99\) a value \(\eta_e > 80\%\) can be attained. The reflection coefficient of the exit mirror \(R_b = 0.99\), from our standpoint, is optimal for achieving high \(\eta_e\), since a further decrease of \(R_b\) increases the threshold value of the gain to a level unattainable in practice.

In our structures the reflection coefficients of the mirrors are close to the indicated optimum: the calculated reflection coefficient is \(R_t = 0.9999\) for the top mirror (neglecting absorption on the free carriers) and \(R_t = 0.9916\) for the bottom (exit) mirror.

We obtained the maximum external differential quantum efficiency \(\eta_e\) at the 60\% level for an LVC with \(A = 4\ \mu\text{m}\). The current–power characteristics of this laser are displayed in Fig. 2a. The decrease of the experimentally achieved value of \(\eta_e\) compared with the 80\% level noted above is due to absorption of about 20\% of the radiation in the 350 \(\mu\text{m}\) \(n\)-GaAs substrate.

Figure 2b shows the current–power characteristics for a laser with a large aperture \(A = 500\ \mu\text{m}\), for which a record high output power was obtained for the LVC (up to 10 W at \(T = 300\ \text{K}\) and 20 W for \(T = 250\ \text{K}\), pulsed regime).

The radiation from all the LVCs we investigated is characterized by a narrow directional pattern. For LVC with aperture \(A = 3\ \mu\text{m}\), the divergence of the laser radiation at the half-power level (the half-width at half-height) is \(\Gamma = 4.7^\circ\), and for a larger-aperture LVC this parameter does not exceed 3\(^\circ\). It is interesting that the radiation of large-aperture lasers operating in a high-power mode is also characterized by a narrow directional pattern. Figure 3 shows the angular distribution of the power of the LVC with \(A = 500\ \mu\text{m}\) with output power \(P = 5\ \text{W}\); the divergence of the radiation is \(\Gamma = 2.75^\circ\).

In summary, the experimental results presented in this letter demonstrate the possibility of building an LVC with high external quantum efficiency and high radiation power. This opens up new prospects for applications of lasers of this type.