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Thermally induced local gain suppression in vertical-cavity surface-emitting lasers

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Joule heating is one of the dominant mechanisms determining the transverse mode formation in vertical-cavity surface-emitting lasers at high injection currents. We give experimental evidence that in this operation regime, strong heating results in local gain suppression in the center of the laser, which overbalances the confining effect of thermal lensing, and thus favors the formation of high order modes. From our investigations of small aperture devices, we conclude that efficient heat removal is crucial for achieving single mode emission at high injection currents. © *2000 American Institute of Physics.* [S0003-6951(00)03123-5]

Oxide-confined vertical-cavity surface-emitting lasers (VCSELs) are state-of-the-art devices for both optical information transmission and scientific applications, because they combine longitudinal single mode emission and high modulation bandwidth with high-quantum efficiency and reasonable low series resistance.[1] Many applications, however, require also transverse single mode operation.[2] Consequently, several aspects of the spatial emission profiles in VCSEL near fields have been investigated, both experimentally and theoretically,[3–7] mostly restricted to low or moderate injection currents. However, the demand for single mode emission at high output powers requires detailed knowledge of the spatial emission characteristics and the underlying mechanisms at high injection currents. Recently, we have identified local gain supression in the center of circular VCSELs as significant mechanism for the formation of high order Laguerre–Gaussian modes at strong pumping.[8] We have given evidence that spatially inhomogeneous pumping originating from the carrier injection via a ring electrode in combination with spatial hole burning reduces the gain in the center of the VCSEL, such that high order modes are preferred. Additionally, there have been strong indications that transverse thermal gradients in the laser contribute to the particular spatial gain distribution. In this letter, we analyze the influence of thermal effects by comparing the results of spatial measurements under both, continuous wave (cw) and low duty cycle pulsed (quasi-cw) operation.

The VCSELs under investigation are the same lasers as used in our former work[8] and are described in detail in Ref. 9. In Fig. 1, we present the power characteristics of VCSELs with 4 and 11 μm oxide aperture diameter, respectively, both for cw and quasi-cw operation with a duty cycle of 2%. The squares represent peak powers for 2-μs-long rectangular current pulses with a 100 μs repetition period, the crosses indicate 0.2 μs/10 μs pulses. For the larger VCSEL, 2 μs/100 μs pulses are sufficiently short to avoid thermal effects as can be seen from the nearly linear P/I curve [boxes, Fig. 1(b)], while the smaller laser requires pulses ten times shorter to avoid thermal saturation. The stronger thermal problems in small-aperture VCSELs have been attributed to higher electrical and optical losses in these devices.[10]

In order to monitor the spatial gain distribution, we follow a similar approach as in Refs. 11 and 12. We record the spatial distribution of spontaneous emission by projecting the VCSEL near field onto a charge coupled device camera and use optical band-pass filters to distinguish lasing emission from spontaneous emission at different wavelengths, both during laser operation. The particular setup is described in detail in Ref. 8. Transverse profiles of these intensity images under cw and quasi-cw operation are depicted in Fig. 2 for the 11 μm aperture diameter VCSEL. The label ''laser'' indicates the profiles of the lasing near fields ($\lambda \approx 800$ nm) while ''lecd'' indicates low energy carrier distributions that have been obtained from spontaneous emission at $\lambda \approx 830$ nm, and ''hecd'' indicates high energy carrier distributions, obtained from spontaneous emission at $\lambda \approx 770$ nm. All graphs are depicted in relative intensity values. Three main features are evident from the carrier profiles: first, the highest carrier density is located at the periphery of the mesa, i.e., directly beneath the ring electrode, whereas the center of the mesa can be reached by carriers via transverse diffusion only. The resulting pump-induced narrow lobes at the periphery are evident in the hecd under both cw and quasi-cw operation. Second, the high output power under quasi-cw operation causes spatial hole burning in the hecd [Fig. 2(b)]. Both mechanisms hardly affect the lecd, as

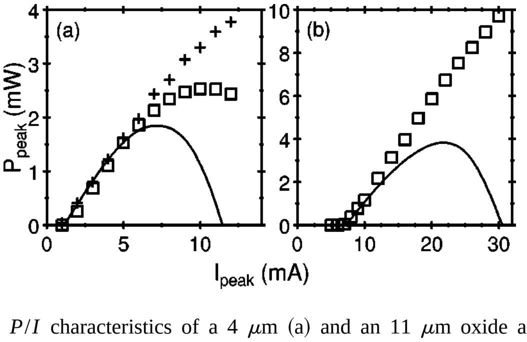

FIG. 1. P/I characteristics of a 4 μm (a) and an 11 μm oxide aperture VCSEL (b). The solid curve indicates cw operation, the symbols indicate pulsed operation using 2 μs pulses (□), and 0.2 μs pulses (+), both with a duty cycle of 2%.

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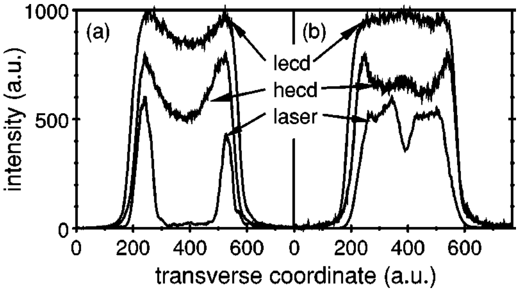

FIG. 2. Near-field profiles of an 11 μm aperture VCSEL under cw (a) and pulsed operation (b) at $I=30$ mA. The curves represent the low energy carrier distribution (lecd), high energy carrier distribution (hecd), and lasing near field (laser).

discussed in detail in Ref. 8. The third feature is a deep and broad central minimum in both hecd and lecd under cw operation. A comparison with Fig. 2(b) (quasi-cw) yields that this local gain suppression is purely thermally induced. Theoretical modeling predicts transverse thermal gradients of several 10 K within the VCSEL mesa already at moderate injection currents.[7,13] Using a simplified model,[14] we even expect gradients of 100 K in the 11 μm VCSEL at $I=30$ mA. We conclude that in the hot center of the VCSEL the carrier confinement within the quantum wells degrades due to thermal escape into adjacent barrier layers. The strength of this effect agrees with the thermionic escape theory.[15] The relative change of the escape times $\Delta\tau/\tau$ from a single quantum well is approximately equal to the negative relative temperature change $-\Delta T/T$. A relative increase in temperature of 30% (from 300 to 400 K), therefore, seems sufficiently large to cause local suppression of 16% in the lecd and of 21% in the hecd. However, a more accurate quantitative estimation of the effect requires detailed modeling. A comparison of Figs. 2(a) and 2(b) yields that thermally induced local gain suppression dominates over pump-induced inhomogeneities and spatial hole burning. Consequently, high order Laguerre–Gaussian modes determine the near field under cw operation, because their mode profiles exploit the gain profile most efficiently. In contrast, in the case of quasi-cw operation the lasing near field is more homogeneous due to the less pronounced structure in the hecd. Therefore, modes with nonvanishing intensity in the center contribute to the near field under these conditions.

This becomes even more evident from the evolution of the lasing near-field profile with increasing injection current, which is depicted in Fig. 3 for the 11 μm aperture VCSEL. In this representation, the abscissa gives the transverse position and the ordinate indicates the injection current. White corresponds to high relative intensity values. The homogeneous profile at $I<7$ mA originates from spontaneous emission. For the case of cw operation (a), the laser emits in the first-order transverse mode at $I\approx 7$ mA and changes to modes of higher order at $I\approx 8$ mA. The highest power density is located near the periphery of the VCSEL at any injection current with secondary peaks in the center which vanish at $I\approx 28$ mA. Furthermore, the outer maxima follow the peaks in the carrier distribution and spread towards the periphery of the VCSEL with increasing injection current. In contrast, for the case of quasi-cw operation the spreading towards the periphery is weaker and the intensity profile is much more homogeneous even at high injection currents due to the more homogeneous gain profile. These features underline our interpretation of the significance of thermally induced local gain suppression.

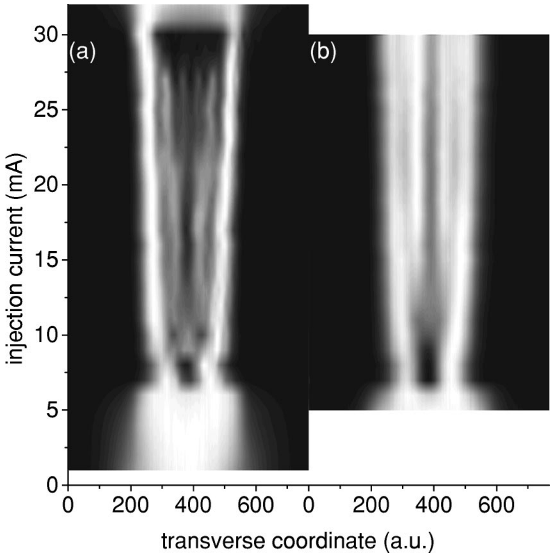

FIG. 3. Near-field profiles of the 11 μm VCSEL depending on the injection current under cw operation (a) and quasi-cw operation (b).

In principle, thermal effects in a VCSEL can show up in a twofold manner: besides local gain suppression, which favors higher order modes, thermal lensing has been identified to confine the optical field in small aperture VCSELs and, therefore, favors single mode emission.[16] We investigate this interplay between both thermal effects by comparing the transverse near-field full width at half maximum (FWHM) of the 4 μm VCSEL under cw and quasi-cw operation (Fig. 4). The circles and solid line indicate cw operation, the crosses and dotted line correspond to 0.2 μs/10μs pulses. At low-injection currents up to 5 mA, where the laser emits in the fundamental transverse mode, the near field under cw operation is narrower than under quasi-cw operation. This is caused by the additional optical confinement due to thermal lensing under cw operation. At high injection currents $I>6$ mA, the near field under cw operation is broadened due to excitation of the first order transverse mode. In contrast, under quasi-cw operation the VCSEL remains in the fundamental mode. Thus, we conclude that thermal lensing is the dominant thermal effect for low to intermediate-injection currents, while local gain suppression determines the emission characteristics at high injection currents, even in com-

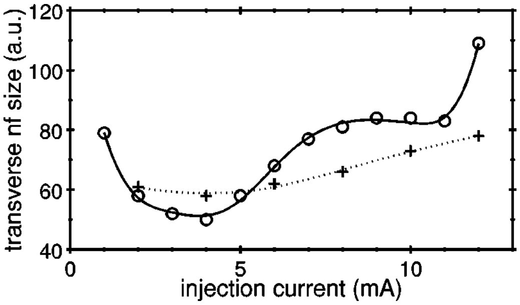

FIG. 4. FWHM of the transverse near-field profile. Solid line and (○) indicate cw operation, dotted line and (+) correspond to quasi-cw operation (the lines are guides for the eyes).

parably small devices. Therefore, an efficient heat removal is crucial to combine both high power and single mode emission in future VCSELs.

In conclusion, we have given experimental evidence that pump-induced heating leads to local gain suppression in the center of VCSELs. At high injection currents, this effect overbalances thermal lensing. Thus, a strong tendency towards the emission of high order modes has been found, because those mode profiles better match the modified spatial gain profile.

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