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Control of optical mode distribution through etched microstructures for improved broad area laser performance

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Etching microstructures into broad area diode lasers is found to lead to more uniform near field and increased power conversion efficiency, arising from increased slope. Self-consistent device simulation indicates that this improvement is due to an increase in the effective internal injection efficiency above threshold—the nonuniform near field leads to regions of inefficient clamping of the carrier density in the laser stripe. Measurements of spontaneous emission through the substrate confirm the predicted carrier profile. Both experiment and theory show that improved overlap between carrier and power distributions correlates with improved slope. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2906030]

Many effects limit the power conversion efficiency of broad area semiconductor diode lasers.[1] Here, we concentrate on the impact of the internal optical modes. In most devices, no effort is made to control the mode structure across the stripe width ("lateral modes"). However, optimizing the mode profile relative to the carrier profile is predicted to improve efficiency by 10% relative to a free-running laser.[2] Other groups have addressed this issue via structuring the current path.[3,4] In previous work,[5] the authors instead used etched microstructures to control the optical field, leading to a more uniform near field together with an increase in power conversion efficiency. Here, we combine diagnostic measurements with full device simulations to determine the potential for further improvements.

We investigated a typical commercial GaAs-based 940 nm device (the structural information has been previously reported[5]) with resonator length of 1 mm and 150-μm-wide p-side contact generated by patterned dielectric layers. Standard metal contact layers were applied to n and p sides of the devices, and the devices were bonded p-(junction) side down on a copper c mount. No optical coatings were used.

In addition to standard processing, the n-(substrate) side metallization over the laser stripe was removed. GaAs is transparent at 940 nm, so the spontaneous emission S of the active region can be directly imaged through the substrate into a Si charge-coupled device (CCD) camera. Current was provided via wire bonds attached at the edge of the device, so as not to obscure the laser stripe.

Electron-hole recombination generates spontaneous emission S via the equation $S=Bn_e n_h$, where B is the spontaneous emission coefficient, n_e is the electron density, and n_h is the hole density.[6] The average carrier density $n_a=(n_e n_h)^{1/2}$ within the laser structure can be determined using $n_a=(S/B)^{1/2}$. Here, we only use the profile and do not attempt to determine absolute values (only a fraction of the emission is collected making calibration challenging). The optical emission profile (near field) was measured by focusing the light from the front facet into a further CCD camera (protected by filters).

The carrier and near field profiles of two different devices taken from adjacent positions on a laser wafer were experimentally compared. One was a simple broad area laser. The second had a microstructure etched into the p side of the device using a focused ion beam[5]—simple lines of $5-\mu$m-wide, $2-\mu$m-deep holes that extended a short distance into the waveguide (see inset of Fig. 1). The microstructure provides additional optical wave guiding for higher spatial frequency transverse modes (in order to generate a more uniform optical profile), but without being strong enough to lead to significant additional total optical loss (no evidence was seen of any performance degradation). The measured optical mode profile from the facet and spontaneous emission from the substrate are shown in Fig. 1 for the two different structures at low and high currents.

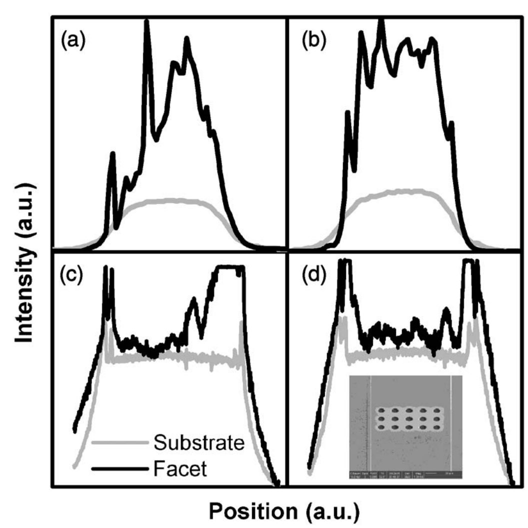

FIG. 1. Measured emission profiles at $0.5I_{\text{th}}$ (gray lines) and $8I_{\text{th}}$ (black lines) from 150 μm stripe broad area lasers with and without p-side patterning. The inset of (d) shows the pattern. (a) Near field (unpatterned sample). (b) Near field (patterned sample). (c) Spontaneous emission from substrate (unpatterned). (d) Spontaneous emission from substrate (patterned).

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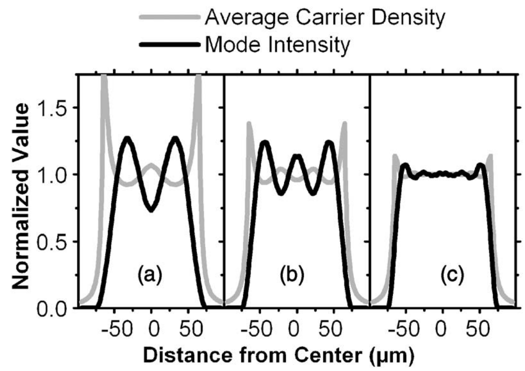

FIG. 2. Theoretical optical intensity and average carrier density profiles for structures with optical profile defined by (a) two, (b) three, and (c) six transverse optical modes at a current of $8I_{\mathrm{th}}$.

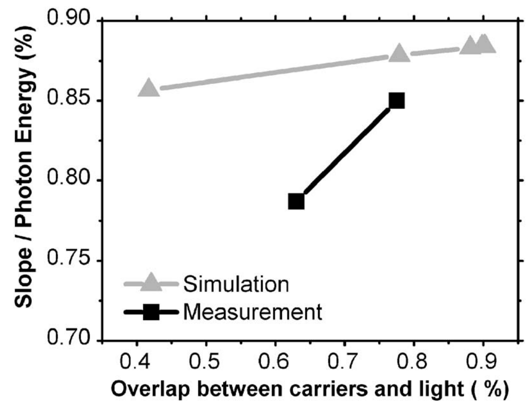

FIG. 3. Normalized slope as function of overlap between optical mode and carrier density—experimental and theoretical.

At low currents ($0.5I_{\mathrm{th}}$ is shown, where I_{th} is threshold current) both devices were found to have uniform spontaneous emission pattern across the stripe, indicating uniform current injection. Both devices also showed increased spontaneous emission at the edges of the stripe. Both devices show uniform optical output.

At high currents ($8I_{\mathrm{th}}$ is shown), the control (unpatterned) sample was found to have highly nonuniform optical emission profile from the facet. The spontaneous emission also becomes highly nonuniform. The device with the etched pattern is significantly more uniform. Both devices show enhanced spontaneous emission from the edges of the stripe at high currents. The slope was $\sim 10\%$ higher in the patterned device, but the threshold was equal.[5]

The degraded slope in the reference device is attributed to its nonuniformity, believed to come from the internal heating effects. Current is injected into the substrate in a small area along one edge of the device, leading to nonuniform heating and an additional refractive index profile—degrading transverse mode uniformity. In the patterned device, we have an additional refractive index profile and we believe that this overcomes the nonuniformity due to the current heating.

In order to better understand the physics underlying these effects, full two-dimensional, self-consistent device simulation was performed.[6] The vertical optical field profile is calculated using one-dimensional effective index calculations. The lateral mode profile is simply represented as a series of transverse standing waves with varying spatial frequency, whose profile is invariant with current and temperature. Here, we use this simple series as a tool to probe the impact of varying optical mode uniformity on device performance.

First, we align our simulation with measurements.[7] As part of this process, the optical near field uniformity is aligned with measurements by appropriate choice of transverse standing waves. We then investigate the impact of an artificial variation in lateral mode profile by altering the number of allowed transverse modes.

In Fig. 2, the simulated average carrier density $n_a = (n_e n_h)^{1/2}$ and near field are shown as a function of the number of permitted transverse modes. All results shown are at high current $I = 8I_{\mathrm{th}}$. In all cases, as the current is increased, the material relatively quickly reaches the threshold condition in the center, stimulated recombination becomes dominant and the carrier density is fixed. For simulations with a low number of modes (with low spatial frequency), the near field is restricted to low intensity at the device edge, and carrier density can continue to build up, increasing the carrier losses. This reduces the internal quantum efficiency η_i and hence slope.[8] As more transverse modes are allowed, a wider region of the material reaches threshold condition and η_i improves. Threshold does not change. Qualitatively, the results align well with experiment—we see enhanced spontaneous emission at the edges of the stripes at high current and degraded slope for material with increased nonuniformity.

This effect can be quantified and compared to the experiment by calculating the overlap O between the optical intensity $\langle I \rangle$ and carrier density $\langle n_a \rangle$ profiles (normalized relative to the device center), using $O = \int_{-\infty}^{\infty} \langle I \rangle \langle n_a \rangle dz$. Values were calculated at $8I_{\mathrm{th}}$. The slope above threshold in W/A was scaled by photon energy in eV to give the external quantum efficiency η_d. Figure 3 shows that η_d is predicted to increase by $\sim 3\%$ as overlap O increases from 40% to 90%. Threshold does not alter.

The same process was then followed using the experimental results, also shown in Fig. 3 (n_a is extracted from the spontaneous emission, as discussed above). The experimental values show the same trend as the simulation, but the size of the effect is larger—possibly due to current spreading.[8] Both theory and experiment indicate that there is room for further device improvement if the overlap can be further enhanced. In future work, we plan to address the source of the discrepancy between theory and experiment and determine how much further improvement is possible.

In principle, equivalent performance is also possible if the current path (contact) is modified instead of the optical profile, and Baoxue *et al.*[4] show a similar (albeit smaller) enhancement in slope with such patterning. However, with increased current heating, the refractive index profile will change and it will be challenging to sustain a given overlap. In contrast, the etched microstructures should be more stable, but are more challenging to fabricate.

Overall, we find that if a broad area diode laser device is held in a nonoptimal optical mode, its slope is compromised due to the areas in the laser that do not reach the threshold condition. The etched microstructures are shown to help eliminate such optical nonuniformity, increasing the slope, in agreement with the device simulation. Simulation and experiment project further improvements for better alignment between near field and carrier density profiles—with the largest effect seen at the device edges.

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