An Investigation of Lateral Current Injection Laser Internal Operation Mechanisms

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Abstract— **Lateral current injection (LCI) lasers have the potential to overcome many of the limitations inherent to conventional vertical injection structures, but until now there has been very little theoretical analysis and optimization of LCI laser designs. 2-D self-consistent simulations of these devices have been carried out to analyze the electrical and optical characteristics of several recently fabricated devices. These simulations are in good agreement with available experimental results and offer explanations for the observed roll-off in differential slope efficiency. In addition, we have explored some key design issues unique to LCI lasers such as the cause and consequences of the non-uniform gain profile, ways to minimize this non-uniformity, and the effects limiting the device speed.**

I. INTRODUCTION

LATERAL current injection (LCI) lasers [1]–[7] have the potential to overcome many of the limitations inherent to conventional vertical injection structures by making use of the under-explored lateral degree of freedom. In an LCI laser (Fig. 1), current does not pass through the optical cladding layers or the substrate, allowing both these regions to be designed for optimal optical confinement and made of wide bandgap semi-insulating material for reduced parasitic loss and capacitance. In addition, the planar geometry of LCI lasers is well suited for OEIC applications.

While there has been a considerable amount of experimental effort devoted to this type of laser [1]–[6], there has, until now, been very little theoretical analysis of the device operation. As a result, the progress of LCI laser development has been rather slow and the best results from the most recent trials are still inferior to that of state of the art vertical injection designs. Typically, the threshold current is high, while the efficiency starts out low and then decreases with increasing current.

It is difficult to determine the origins of these shortcomings from experimental measurements alone. Many interdependent factors are involved, some of them uniquely new. Starting from fundamental laser physics the job is no easier. First principle considerations may be the same as for vertical injection, but new aspects of the electrooptic interaction are involved which require self-consistent analysis. This is what we have done using our 2-D self-consistent finite element light emitter simulator (FELES) [8].

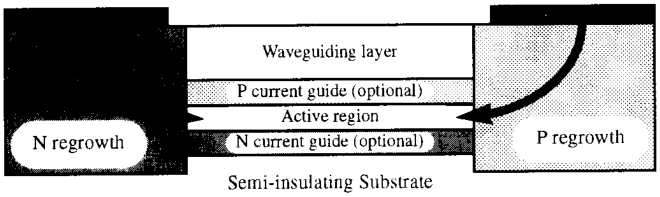

Fig. 1. A regrown buried heterostructure LCI (BH-LCI) laser design. Arrows indicate direction of current injection from the contacts into the active region. The axes correspond to the directions used in the following figures.

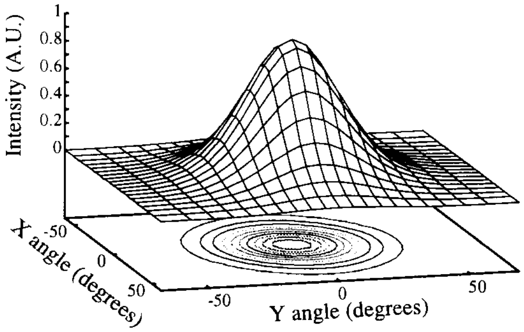

Fig. 2. Calculated far field pattern for an InP–InGaAs–InAlAs MQW LCI laser [5]. The FWHM angles are 48° in the X direction and 41° in the Y direction.

II. ANALYSIS

We will concentrate on the analysis of a pair of 1.5-μm buried heterostructure LCI (BH-LCI) lasers (Fig. 1) that were recently reported in the literature [5], [6]. In the first of these structures [5], carriers are laterally injected from regrown n- and p-doped InP into a InGaAs–InAlAs MQW active region. One of the advantages of this type of design is the good carrier and optical confinement achievable in both transverse directions. Since the cladding layers outside the active region are not electrically active and serve only to guide the wave, the compositions and widths of these layers, as well as that of the active region, can be designed to produce a single transverse mode that exhibits an almost perfectly circular far field pattern (Fig. 2) without compromising the electrical characteristics of the device.

The investigation of this structure also reveals a key design issue unique to LCI lasers. The lateral gain profile in the QW's is not uniform (Fig. 3). This problem, which can only be seen clearly through simulation, was found to originate from

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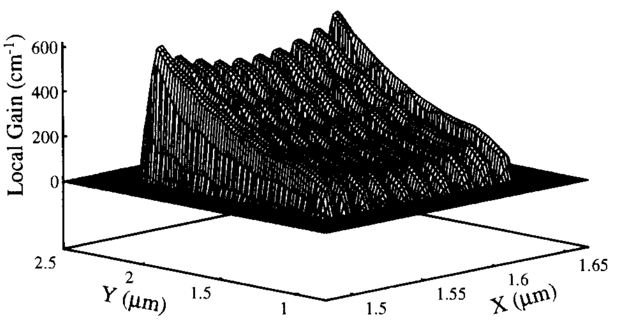

Fig. 3. Simulated gain profile showing non-uniformity due to electron and hole mobility differences for an InP–InGaAs–InAlAs MQW LCI laser [5]. In the plot, 10 QW's are contacted by an n-type regrowth at $Y = 1.0$ μm and a p-type regrowth at $Y = 2.2$ μm. The effects of spatial hole burning in X and Y are also visible.

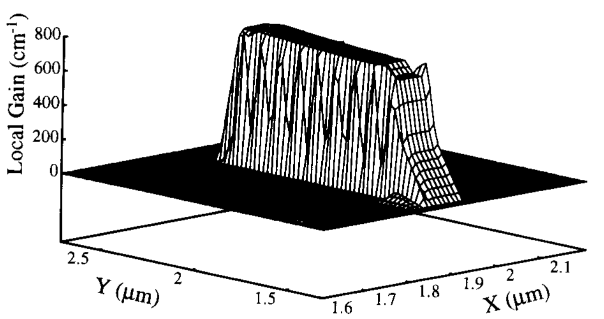

Fig. 4. Simulated gain profile for an LCI laser with current guiding layers [6]. A 0.1-μm thick active region extends from the n-type regrowth at $Y = 1.5$ μm to the p-type regrowth at $Y = 2.5$ μm. The region above the active layer ($X < 1.8$ μm) is p-type and the region below ($X > 1.9$ μm) is n-type.

the disparity in mobilities between electrons and holes. To maintain quasi-charge neutrality, the higher mobility electrons tend to be pulled over to meet the lower mobility holes and to "pile up" near the p-doped/active region interface, resulting in a highly asymmetric gain profile which decreases the overlap of the optical mode and the gain peak, and ultimately increases threshold and lowers efficiency. In a structure which is multimode at zero bias (or becomes multimode due to bias dependent changes to the refractive index), the nonuniform gain profile will selectively pump higher order modes and could even cause them to lase before the fundamental mode. This was confirmed in one of our own preliminary experimental trials.

A promising design approach for minimizing this problem was implemented in a second BH-LCI laser [6]. In this device, regrown n- and p-doped InP regions inject carriers into an InGaAsP bulk active layer ($\lambda_g = 1.5$ μm) through doped InGaAsP ($\lambda_g = 1.3$ μm) "current guiding" layers above and below the active region. Addition of these current guiding layers results in a design which is a lateral/vertical injection hybrid. Current is not only injected from the ends of the active region as in previous lateral injection designs, but also along the length of the channel, as is the case for vertical injection lasers. While the injection paths are now more similar, the differences in fabrication and contacts remain. No current flows through the top cladding layer or the substrate and the geometry is still planar, so the benefits of lateral injection are retained. Our simulations revealed that the use of these thin current guiding layers produces a more uniform gain profile (Fig. 4), but at the cost of increased leakage. This is a problem that is specific to particular structures and simulations of design variations and can be used to study this trade-off and optimize the design.

We simulated the external characteristics of this structure using FELES and found the predicted single-mode operation, threshold current, and L-I characteristics to be in good agreement with experiment (Fig. 5). An especially striking feature of the experimental results is the steady decrease in differential efficiency with increasing current. This leads to output power saturation at a relatively low level: Only 10 mW at a current of 150 mA. Speculations based on inspection were made regarding the possible causes of this roll-off, including high nonradiative recombination at the regrowth interface and carrier leakage in the lateral direction.

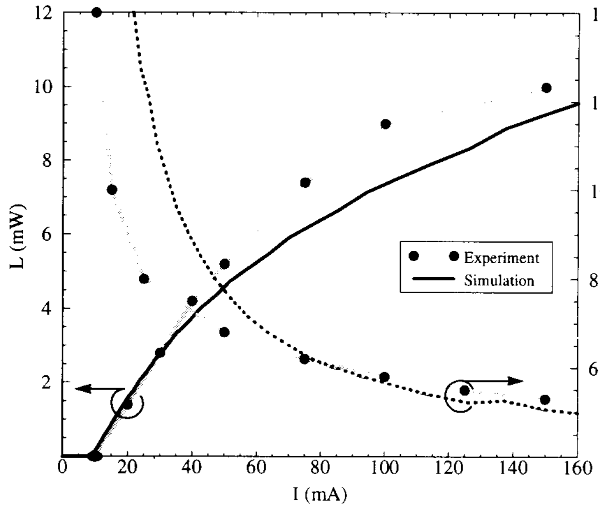

Fig. 5. Experimental and simulated L-I and differential resistance curves for an LCI laser. The laser design and experimental data were taken from [6] and the simulation results were produced by FELES.

To test the possibility that the steady roll-off was due to a high-defect density at the regrowth/active region interfaces, narrow (0.1 μm) regions with high nonradiative recombination rates were added to the simulations at these interfaces. These results showed a slight increase in threshold and a decrease in peak optical output power, but even lifetimes as short at 10 ps did not significantly alter either the threshold or the efficiency. This can be explained by the fact that the actual area of the vertical regrowth interface through which the current flows is very small and is perpendicular to the direction of current flow. This makes its total effect much smaller than that observed in conventional DFB or buried heterostructure lasers for a given defect density.

We next considered the possibility of carrier leakage out of the active region in the lateral direction. Simulations allowed us to examine the current components in the device and revealed that at a bias of 150 mA, less than half of the terminal current was passing through the active region. Since more than half of the current was never even getting into this area of the device, leakage out of this region could not possibly be the explanation of the decrease in differential slope efficiency.

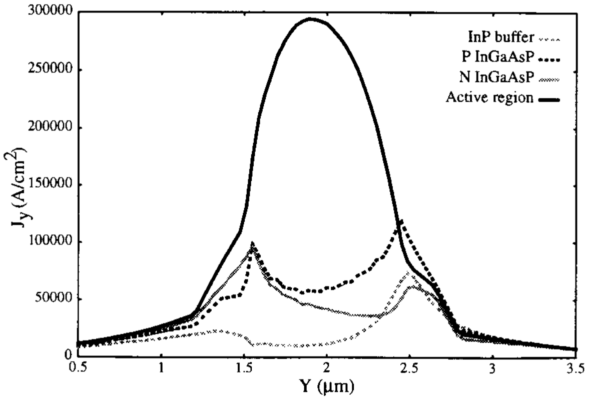

Fig. 6. Simulated current densities in various cross sections perpendicular to the growth direction of the LCI laser reported in [6]. N-type regrowth is present for $Y < 1.5$ μm and p-type for $Y > 2.5$ μm.

Further simulations showed that leakage current was the major cause of the roll-off, but not the type of out-of-well leakage that is typical of vertical injection lasers. Instead, this decrease in efficiency with bias is mostly due to the activation of parallel conduction paths through the guiding layers and the InP buffer. These layers form wide bandgap diodes that are electrically in parallel with the active region. Since the turn-on voltages of these diodes, especially the p-i-n diode formed between the regrowth regions through the InP buffer layer (~1.35 V), is much larger than the turn-on voltage across the active region (~0.85 V), one might not expect leakage to be a problem. Indeed, this is true for injected currents up to a few mA's as attested to by the low threshold currents of both the experiment and simulation. Under high injection, however, the voltage drop becomes sufficient to bias these parallel diodes near their turn-on voltages. This activates these parasitic conduction paths (Fig. 6) and results in an exponential increase in leakage current and a corresponding decrease in efficiency.

When the leakage problem is minimized, our analysis indicates that BH-LCI lasers should be comparable to vertical injection lasers in terms of threshold and slope efficiency. Another consideration which naturally arises is the device speed. This is a complex and challenging subject involving such issues as 3-D to 2-D capture processes and ambipolar transport in 2-D space. Our initial investigation into this question indicates that LCI lasers have, at least, the advantage of low parasitic delay.

Since the substrate can be made semi-insulating, the effective area of the n- and p-contacts is small and the separation between the contacts is relatively large, the capacitance of LCI lasers should be much lower than vertical injection designs. In confirmation of this, FELES simulations predict a zero bias capacitance of 0.8 pF for the structure reported in [6], compared to the 0.5 pF measured experimentally. While it is difficult to experimentally measure the capacitance under large forward bias, it was easily determined from FELES simulations and found to be approximately 15 pF with the device biased at twice the threshold current.

In addition, perhaps contrary to one's intuition, both experiment and simulation results exhibit a low differential resistance (Fig. 5). This can be explained by the fact that although the conduction path through the active region is narrow, it is composed of high mobility, low bandgap material. In contrast, the conduction path in conventional lasers is quite wide but passes through the large bandgap, low mobility cladding layers.

III. CONCLUSION

In summary, our analysis shows that LCI lasers have the potential to be low-threshold, high-performance components suitable for OEIC applications. While the performance of experimental devices produced until now have not yet been competitive with conventional vertical injection lasers, our simulations have led to an improved understanding of the problems encountered and indicate ways in which some of these problems can be overcome.

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