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Advanced Laser Diodes for Sensing Applications

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Prepared by

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Advanced Laser Diodes for Sensing Applications

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Abstract

We have developed diode lasers for short pulse duration and high peak pulse power in the 0.01-100.0 ns pulsewidth regime. A primary goal of the program was producing up to 10 W while maintaining good far-field beam quality and ease of manufacturability for low cost. High peak power, 17 W, picosecond pulses have been achieved by gain switching of flared geometry waveguide lasers and amplifiers. *Such high powers are a world record for this type of diode laser.* The light emission pattern from diode lasers is of critical importance for sensing systems such as range finding and chemical detection. We have developed a new integrated optical beam transformer producing rib-waveguide diode lasers with a symmetric, low divergence, output beam and increased upper power limits for irreversible facet damage.

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Nomenclature

PCSS	PhotoConductive Semiconductor Switch		
COD	Catastrophic Optical Damage		
Q-switch	modulation of the efficiency of a laser cavity		
I_s	gain saturation optical intensity of light in a quantum well		
P_{lim}	Limiting power output of a diode laser		
Γ	Relative optical confinement of light in a quantum well		
α	Loss per unit length of light in a waveguide		
G	optical gain per unit length of light in a waveguide		
QCSE	Quantum Confined Stark Effect		
MQW	Multiple Quantum Well		
QW	Quantum Well		
VLOC	Very Large Optical Cavity		
TRAFFiC	Tapered Rib Adiabatic Following Fiber Coupler		
ps	10^{-12} seconds	μ s	10^{-6} seconds
ns	10^{-9} seconds	W	Watts, SI unit of power
nJ	10^{-9} joules, SI unit of energy	μ m	10^{-6} meters
cm ⁻²	inverse square centimeters	mm	10^{-3} meters

Background and Motivation

Several experimental systems under investigation at Sandia have exposed a common deficiency in existing pulsed laser technology. Systems which use high-power pulsed lasers are: active optical sensors, laser range finders, 3-d laser radar, optical ignition (fuels and explosives) and high-speed photo-conductive switch (PCSS) triggering. The bulk of these applications require a minimum of 10 W peak optical pulse power in a stable single-lobed far-field radiation pattern over a range of pulse widths from 50 ps to 100 ns. Some of these could use somewhat less power. Such pulses (with the exception of the shortest widths) are currently obtained from large, expensive, Q-switched lasers. However, many of these applications require low-cost, highly reliable devices which could be produced with semiconductor laser technology if the peak power requirements could be met. Diode lasers meet the cost criteria but are not able to deliver the required peak pulse power. In order to bridge the gap between available technology and application needs, we have explored new diode lasers for short pulse duration (0.1 to 100ns) and high energy (up to 100nJ) while maintaining good far-field beam quality and ease of manufacturability for low cost.

Maximum power output from diode lasers for pulse duration greater than ~1 ns but less than ~0.5 μ s is determined by the saturation intensity, I_s , of the gain medium and the catastrophic optical damage (COD) limit of the cleaved laser facets. For longer pulse duration thermal effects further reduce the maximum power while shorter pulses can exceed these two limitations as the injected carrier populations are not allowed to reach thermodynamic equilibrium. The saturation intensity and subsequent power limit may be expressed as,

$$I_s [\text{W cm}^{-2}] \propto (\text{e-h pair recombination lifetime})^{-1} (\text{differential gain})^{-1}$$

$$P_{\text{lim}} = (I_s w d / \Gamma) (g / \alpha - 1)$$

where w and d are the thickness and width of the active media respectively, Γ the optical confinement factor, g the modal gain and α the modal loss. Lasers operating in a stable fundamental mode typically have $w < 10 \mu\text{m}$, $d < 50 \text{ nm}$, $\Gamma \sim 0.15$, $(g/\alpha - 1) < 30$ and $I_s = 5 \times 10^5 \text{ W cm}^{-2}$. This limits a conventional $10 \mu\text{m}$ -wide single mode laser with multiple quantum wells to $P_{\text{lim}} = 1.0 \text{ W}$. An accepted lower COD limit for cleaved facet lasers without any special treatment is $\sim 2.5 \text{ MW/cm}^2$. This translates to an output power of 375 mW for 10 by $1.5 \mu\text{m}$ emission area. The above estimates are in good agreement with the current published state of the art. The highest single-rib laser output power is 700 mW from a $7 \mu\text{m}$ wide device using a nonabsorbing mirror technology to elevate the COD limit. With conventional facets, the highest published output is 500 mW.

Pulses $< 500 \text{ ps}$ in duration can be generated using gain (Q-) switched diode lasers. The pulse energy and duration from a gain switched laser is determined by the carrier density injected above threshold before the onset of lasing. This is limited by parasitic capacitance in the laser and the maximum laser current and voltage at which damage occurs due to failure

of current confinement structures, metallizations, etc. In practice, this generally results in pulse energies approaching 10 pJ with pulsewidths of 10-100 ps, giving peak powers approaching 1 Watt. Because no resonant cavity is involved, gain switching at varied repetition rates is easily achieved. Prior to this work, maximum published power levels from gain and Q-switched devices were limited to about 6.6 W peak pulsed power in a sub 50 ps pulse width.

Flared waveguide laser designs (Fig. 1.1) address key issues in the generation of high optical power from diode lasers. The flared waveguide expands the optical mode from a narrow region that constrains lasing to a single lateral optical mode, to a wider multimode region for higher power. The saturation energy can be made relatively large at the flared output end of the amplifier. By expanding the gain cross-section area along the length of the amplifier, as the amplified power grows, a more uniform power density and degree of gain saturation is maintained throughout the amplifier. The mode expansion within such a device occurs via lateral diffraction, at a full angle of about 6° starting from a standard single-mode waveguide. For reasonable device dimensions of up to 5-mm length, this results in an output aperture of 525 μm , or over two orders of magnitude mode expansion compared to the single mode portion of the device. The COD theoretical power limit of such an emission aperture is on the order of 50W, with pulse saturation energy of 0.5 nJ. Such large gains in pulse energy and peak power are clearly attractive to a variety of Sandia and DOE programs.

Figure 1.1: MOPA (top), gain- (Q-) switched multi-segment (middle) and gain-switched single segment lasers. All have flared waveguide output section. The MOPA device is characterized by the reflective facet or grating placed between the laser and flared amplifier. The other two devices have the flared section integral to the laser cavity.

The research effort summarized in this report is focused on development a variety of laser designs capable of peak pulsed output powers up to 10 W over a range of pulse widths from 50 ps to 100 ns. High-peak-power picosecond pulses will be achieved by gain switching of flared geometry waveguide lasers and amplifiers. Mode expansion in the flared section is achieved while maintaining fundamental mode operation, resulting in diffraction-limited far field beams suitable for ranging or applications requiring tight focusing.

Improved theoretical understanding of short-pulse dynamics has also been used to increase peak output of short-pulse lasers. In such devices, the spectral and temporal properties of the inverted carrier distribution affect the modal and dynamic behavior of short-pulse semiconductor lasers. These issues are presently understood in terms of the time response of quasi-equilibrium carrier distributions. However, with the short pulse duration we propose to achieve, non-equilibrium carrier dynamics can play an important roll. We will address, numerically, the non-equilibrium carrier dynamics issues affecting short-pulse laser operation. The goals of these investigations are to understand the dynamic response of the coupled photon/carrier system in gain switched or mode-locked semiconductor lasers and develop numerical laser models for optimizing pulsed laser design.

In addition to work with 1-D flared lasers, techniques have been developed for 2-D optical mode expansion with the intent of raising the COD limit. Diode lasers with 2-D expanded optical modes will have dramatically reduced the far-field divergence and no COD limit in an otherwise moderately confined rib waveguide laser. We call the 2-D expansion section a TRAFFiC waveguide (see later chapter in this report). With the TRAFFiC laser, a 4- μm -wide rib waveguide is placed between two TRAFFiC structures at the cleaved output facets. The resulting laser combines the attributes of a moderately confining, narrow, rib (low threshold current and stable fundamental mode operation) with the benefits of a large output mode size (reduced beam divergence and lower peak intensity at a given output power.) Maximum output power will be limited to roughly 450 mW due to the narrow rib and high Γ value. This maximum power is one-fourth COD limit of the 8 μm by 10 μm output facet. Under gain-switched operation the TRAFFiC laser may be capable of several watts peak pulse power with a narrow, symmetric, far field divergence of $\sim 7^\circ$ FWHM.

High Peak Power Gain Switched Flared Waveguide Lasers

Introduction

Obtaining high peak powers and energies from pulsed single-mode semiconductor lasers is highly attractive for many applications requiring compact sources of picosecond pulses of high beam quality. In this section, we develop gain-switch a flared waveguide laser to obtain high peak powers and pulse energies from a single laser diode without post-amplification. The flared waveguide expands the optical mode from a narrow region which gives a single lateral optical mode, to a wider multimode region for higher power. Flared laser amplifiers have previously been used for mode-locking [1,2], Q- and gain-switching[3,4] of diode lasers. Flared structures have also been utilized for post-amplification[5,6] to achieve high peak power. Gain switching offers a considerable advantage in terms of simplicity over mode-locking, in that no resonant cavity is required to be synchronous with the electrical drive, while the external amplifier approach requires additional alignments. High single-mode peak powers have also been obtained from single-heterostructures with ion implanted saturable absorbers[7]. Increased gain-switched peak powers are obtained from single-heterostructures due to the increased active layer volume and large lasing turn-on delays, which allows the use of slower, higher energy electrical pulses to drive the gain-switching. The use of the flared amplifier approach also increases the active region volume, while retaining the advantages of carrier confinement and mode control in a double heterostructure single-quantum well active region. High-voltage subnanosecond electrical drive pulses are used with a reverse-biased saturable absorber section in the laser to obtain gain-switching. Numerical simulations based on a microscopic laser model verify the effectiveness of the saturable absorber in the generation of high peak power, single-pulse output. Insight obtained from the model suggests that the quantum-confined Stark effect (QCSE) is primarily responsible for saturable absorber operation.

Laser Fabrication

The flared waveguide gain-switched lasers utilize a dry-etched AlGaAs double heterostructure rib waveguide with a single quantum well active region, and a lasing wavelength of 850 nm. As shown in Figure 2.1, a short single-mode section of the laser waveguide is biased separately to function as a saturable absorber or modulator. Oxygen ion implantation was used to create an electrical isolation region between the single-mode and flared sections. The flared devices have linear tapers from 4 μm to 150 μm over a 1500 μm distance, and lengths of single-mode waveguide/absorber section varying from 30 to 100 μm were tested. Silicon nitride is deposited on the output facet to reduce the reflectivity to $\sim 5\%$ for increased output coupling.

Figure 2.1: Diagram of flared waveguide laser with saturable absorber for gain-switched operation.

Laser Testing and Results

Gain switching is achieved by applying electrical pulses to the flared amplifier while applying reverse bias to the saturable absorber segment of the laser. The optical output was measured using a fast photodetector (~ 17 ps impulse response) and 50 GHz sampling oscilloscope. As shown in Figure 2.2, the gain-switched operation is very sensitive to the speed (pulsewidth) of the electrical excitation. As the electrical pulsewidth is shortened from 0.97 to 0.54 ns, the optical output evolves from a series of multiple pulses with most of the pulse energy outside of the main peak, to a single clean gain-switched pulse. In this sequence, the peak optical power remains fairly constant as the electrical pulsewidth (and therefore energy) is reduced. In this case the peak voltage applied was 100 V, and the saturable absorber bias held at 0V. At lower peak voltages, single pulse gain-switching was obtainable with longer electrical pulses (at lower peak powers and pulse energies). This indicates the need for increasingly faster electrical pulses to obtain gain switching at higher powers.

Figure 2.2: Data resulting from a series of tests of gain-switched flared lasers with different input pulse duration. The shortest pulse tested resulted in a sharp single pulse of only ~35 ps duration without multiple output pulses.

Figure 2.3: Effect of saturable absorber bias on pulse shape.

The effectiveness of the reverse-biased saturable absorber in generating short (~ 33 ps), single pulses with increased peak power is demonstrated in Figure 2.3. In this case, the longer (0.97 ps) electrical pulses as in Figure 2.2a are applied, but the saturable absorber bias has been increased to -9V. The increased saturable absorber bias enables clean single-pulse gain switching with the longer electrical excitation. As most of the pulse energy is now in the single main peak, the peak power has increased from 3.7 to 9.2 W with a pulse energy of 480

pJ. (The peak powers measured in this paper were precisely obtained by numerical integration of the detected pulse shape and normalizing that integral to the pulse energy, which is determined very accurately by measuring the average power and repetition rate of the laser. Note that these figures differ appreciably from those obtained by simply dividing the pulse energy by the FWHM pulsewidth, as is often done.)

Figure 2.4: Simulation of the carrier concentration within the flare section 1227 ps after initiation of the electrical injection.

As seen in Fig. 2.3, excellent qualitative and quantitative agreement between the measurements and calculations is observed. The calculation was performed at University of Arizona and included time resolved microscopic effects of carrier heating and population inversion on the operation of the laser. Figure 2.4 is an example of the insight gained from use of the simulations. This is a plot of the carrier density within the flare section 1227 ps after initiation of the electrical drive pulse. Non-uniform carrier depletion can be seen at the edges of the flare section near the output end of the device. This result suggests that our

current flare shape is not making best use of the injected carriers, possible due to lateral diffraction within the flare not being adequate to fill the exit aperture of the flare.

The above results were obtained with a variable (amplitude and pulsewidth) electrical pulser with a peak voltage of 100V. To obtain still higher power and pulse energy, a fixed pulser with 863 V peak voltage and 544 ps pulsewidth was installed into the experiment. The output of this pulser was attenuated to the point that single-pulse gain switching was achieved, with higher voltages resulting in multiple pulse operation as described above. Figure 2.5 shows the result of applying 173 V to the laser. The peak optical power is 15.9 W, with a pulse energy of 1.39 nJ. At this power level, no damage to the lasing facets was observed, and higher peak powers and pulse energies are expected with the use of faster, higher power electrical pulses.

Figure 2.5: 17 W peak power and 1.4 nJ total pulse energy from a gain-switched flared laser. This result was obtained with a 173 V drive pulse and is a world record for pulse energy from lasers of this type.

Tapered Rib Adiabatic Following Fiber Couplers in Etched GaAs Materials for Monolithic Spot-Size Transformation

Introduction

Improving the far-field radiation pattern and increasing the COD limit of high-power lasers both may be achieved by increasing the output optical mode size compared to that of conventional diode lasers. A 2-D expansion of the optical mode is made complex by the fact that crystal growth technologies forming the basis of laser diode fabrication are heavily biased toward forming planar (laterally invariant) epitaxial layers. A high degree of synergy exists between the technical challenges of spot-size transformation for high-power and those of spot-size transformation for fiber-optic communications. Practical upper limits on modal spot size are imposed by considerations of total epitaxial material thickness and stability of the large fundamental mode shape against non-idealities in the grown waveguide. The 8 to 10 μm spot of a telecommunications optical fiber is essentially the largest spot practically achievable for high-power and remote sensing applications. Simple and very accurate comparisons may be made between our technology, developed for high-power applications, and competing technologies, developed primarily for fiber-optic communications uses. To facilitate such comparison and promote understanding of our technology, we have written this chapter with a considerable focus on fiber coupling issues. However, in all cases, far-field data detailing the high degree of optical beam collimation achieved using our technology is presented.

High performance optoelectronic systems using optical fiber signal routing require low-cost and low-loss coupling between single-mode fibers and active or passive semiconductor waveguide devices and circuits. However, the 1-3 μm elliptical modal spot of typical semiconductor waveguides is poorly matched to the 8-9 μm circular modal spot of conventional single-mode optical fibers. This modal mismatch results in a 7-10 dB insertion loss when directly coupling light between these single-mode fibers and semiconductor waveguides. Non-integrated solutions that improve this coupling efficiency often do so at the cost of tight alignment requirements and are thus not well suited for low-cost package using passive alignment systems.^[8] Tapered waveguide transitions^[9-17] offer a monolithically-integrated means by which efficient coupling can be achieved with relaxed alignment requirements. Most of these approaches, however, require complex growth or processing steps such as multiple etch-regrowth sequences or lithographic patterning of extremely small radius waveguide tips in order to achieve the desired coupler performance. Because of these limitations, a new class of tapered mode expander^[18-20] has been developed requiring only a single epitaxial growth and etch. Two of these^[18,19] have demonstrated less than 1 dB coupling loss to single-mode fiber.

We describe here the Tapered Rib Adiabatic Following Fiber Coupler^[18,19] (TRAFFiC) and its application to both passive optical modulators at 1.3 μm wavelength and active diode

lasers at 0.98 μm wavelength. All of the TRAFFiC structures achieve less than 1 dB coupling loss to single-mode fiber at the design wavelength and may be fabricated with a single epitaxial growth step followed by conventional lithography and etch steps.

This section is structured as follows: First the theoretical basis of the TRAFFiC device is explained using a generic doped *pin*-diode waveguide as an example. Spot-size transformation efficiency is calculated at different tapered rib waveguide etch depths and for etched ribs with rounded bases. Excess loss and fiber coupling performance data is then presented for TRAFFiC devices fabricated using the example design. Then, using the *pin*-waveguide as a starting point, a 980 nm wavelength InGaAs/AlGaAs diode laser design is presented and performance data of fabricated TRAFFiC lasers is shown.

Design Concepts and Method for Adiabatic Mode Expansion of Etched Rib Waveguides

One particular design of a TRAFFiC device, intended for use with a *pin* junction optical phase modulator at 1.3 μm wavelength, is shown in Fig. (3.1). In this figure, a small rib waveguide is located on top of a thick lower cladding which is partially etched to form a mesa structure. When the small rib is sufficiently wide the fundamental optical mode is confined to the small rib (Fig. 3.2a) and the device functions as an efficient modulator with high confinement of light within the undoped GaAs layer. At the other extreme, when the small rib is sufficiently narrow, the fundamental mode expands to fill the larger mesa waveguide (Fig. 3.2c). This behavior is a consequence of the design of the waveguide layers. The thickness and composition of the GaAs and graded AlGaAs layers at the top of the mesa and extending under the small rib are such as to prevent guiding of light^[21] within these layers if the upper layers comprising the small rib are etched away. The resulting waveguide allows separate optimization of the optical mode properties of the rib and mesa waveguides at the two extremes of rib width. At large rib widths high-performance modulator function can be achieved while at small rib widths the dimensions of the large mesa and thickness of the lower cladding materials establish the optical mode size of the mesa waveguide for optimum coupling to single-mode fiber. The expanded mode (Fig 3.2c) has been designed for optimum coupling directly to single-mode 1.3 μm telecommunication fiber. Modal overlap integral calculations predict greater than 90 percent power coupling between the expanded mode and an 8 μm mode diameter optical fiber.

Figure 3.1: a) Cross section diagram of TRAFFiC device for high-efficiency *pin* modulator application at 1.32 μm wavelength. b) Top view of waveguide taper configuration showing orientation of taper to single-mode optical fiber.

Figure 3.2: Contour plots of constant field of eigenmodes at three different TRAFFiC taper widths. a) Wide rib with small spot size. b) Intermediate rib with spot size in transition. c) Narrow rib with large spot size.

Numerical modeling is required to ensure that the mode expansion occurs with a minimum of excess loss. Selection of the most appropriate modeling tool requires consideration of the actual fabrication method and its influence on the final waveguide topology. The TRAFFiC structure is fabricated using electron-beam direct write or optical contact print lithography followed by highly anisotropic reactive-ion-beam etching (RIBE)^[22]. These techniques result in a waveguide taper comprising abruptly joined straight segments whose widths progressively decrease in precise (e.g. 0.025 μm) steps. An example of a stepped taper is shown in Fig. 3.3. The modal evolution of such a waveguide made up of longitudinally invariant segments is well described using a 2D finite-element model to find the fundamental mode at each segment along the taper provided that the taper slope is sufficiently gradual. The radiation loss of the taper can then be calculated using modal overlap integrals to estimate the coupling efficiency across each step and then multiplying all of the individual step-coupling efficiencies to determine the overall power-conversion efficiency. For low-loss waveguides, this radiation loss is the excess taper loss. Such an approach is computationally faster than 3D beam-propagation method and provides accurate eigenmode solutions at each rib width. All 2D modal calculations employ a variable mesh size between 20 and 200 nm with finer meshing used at refractive-index discontinuities.

Figure 3.3: SEM image of tapered rib waveguide showing discrete 0.025 μm steps in rib width. This particular rib was made very short in order to obtain this image.

Figure 3.4: Individual step coupling efficiency through the taper in Fig.(3.1) as a function of segment width.

Figure 3.4 shows the individual step coupling efficiency through the taper in Fig.(3.1) as a function of segment width. Steps are $0.025 \mu\text{m}$ and alternate between the left and right sides of the taper. For large rib halfwidths, the mode is confined to the small rib as seen in Fig. (3.2a) where the halfwidth is $1.2 \mu\text{m}$. As the rib sections narrow, the segment-to-segment coupling is high and varies only slightly with width until the halfwidth reaches roughly $0.7 \mu\text{m}$. The flat coupling efficiency for large halfwidths results from the mode shape changing only slightly in this section of the taper. Below $0.7 \mu\text{m}$ halfwidth the mode begins to change shape more rapidly and gradually shift power down into the lower mesa below the rib. Figure (3.2b) shows one of these transitional modes. The changing mode shape and peak intensity location results in a dip of the segment-to-segment coupling between $0.7 \mu\text{m}$ and $0.3 \mu\text{m}$ halfwidth. Below $0.3 \mu\text{m}$ halfwidth the mode is largely confined in the mesa waveguide (Fig. 3.2c) such that further reduction of the small rib width has little influence on the optical mode. Completion of the mode expansion into the large mesa

waveguide occurs at significantly large rib widths which can readily be resolved using conventional optical contact lithography. In the present example mode expansion is complete when the rib halfwidth is $0.3\text{ }\mu\text{m}$. In fact, the rib may be abruptly terminated at any fullwidth below $0.7\text{ }\mu\text{m}$ without significant penalty. Overall taper radiation loss is the product of all the individual segment-to-segment coupling efficiencies. In the present example this is 85.7 percent (equivalent to 0.67 dB radiation loss). A three-dimensional beam propagation calculation was used to benchmark the successive modal overlap model and to aid in selecting a taper length for good mode conversion. Results of this calculation are in good agreement with the successive modal overlap model and suggest that tapers with $>500\text{ }\mu\text{m}$ length have the desired $<1\text{ dB}$ theoretical radiation loss.

Figure 3.5: TRAFFiC radiation loss versus minimum pixel (or step) size used to pattern the tapered rib waveguide.

The two key physical parameters influencing the power conversion efficiency are the step size used in patterning the taper and the etch depth of the rib. Additional modeling has shown that the excess loss of the taper expressed in dB is essentially linearly proportional to the step size used in creating the taper (Fig. 3.5). It is this dependence of radiation loss on sidewall step size that has prompted the use of electron-beam direct write in the initial demonstration of the TRAFFiC waveguide. Although the minimum dimensions of the taper are within the capabilities of conventional contact lithography, the step size of $0.025\text{ }\mu\text{m}$ required for less than 1 dB excess loss is not available from commercial mask vendors without the use of a reducing reticle. Fabrication of a different TRAFFiC design using conventional contact printing with a specially-made photolithographic plate is described later in this section.

Figure 3.6: Power transfer efficiency of spot-size transformation as a function of rib waveguide etch depth. Depths are relative to the rib depth shown in Fig. (3.1).

Figure 3.7: Individual step coupling efficiencies through the taper in Fig.(3.1) as a function of segment width for a variety of different rib waveguide etch depths. Depths are relative to the rib depth shown in Fig. (3.1).

Variation of excess loss with etch depth of the small rib is shown in Fig. 3.6. Power conversion efficiency drops linearly with etch depth from the best value of approximately 86% down to only 60% for etching 0.4 μm deeper than shown on Fig 3.1. Careful examination of the individual step coupling efficiencies of tapers with different etch depths (Fig. 3.7) provides some insight into the function of the TRAFFiC waveguide. As is clearly evident in Figure 3.7, as the etch depth is increased the transition point where the greatest variation in the mode shape occurs moves to larger rib sizes. Movement of the transition point to larger rib sizes for deeper etches is a result of the reduced modal effective index of the more deeply etched ribs approaching the effective modal index of the eventual mesa mode more quickly as the rib narrows along the length of the taper. In addition the mode evolution tends to “snap” more quickly from confinement in the rib to confinement in the mesa. In other words, the bulk of the mode transition occurs in just a few segments of the

TRAFFiC waveguide and these few transitions have reduced coupling efficiency. Etching $0.1\text{ }\mu\text{m}$ less deeply than shown in Fig. 3.1 (a relative etch depth of $-0.1\text{ }\mu\text{m}$ in Figs 3.6 and 3.7) results in confinement of the expanded optical mode by the layers at the top of the mesa and no vertical mode expansion. Calculated power coupling efficiency of the expanded-mode waveguide output into an $8\text{-}\mu\text{m}$ spot size ($1/e^2$ intensity diameter) single-mode optical fiber remains between 91.7 and 93.7 percent for all the waveguides plotted in Fig 3.6

Figure 3.8: Individual step coupling efficiencies through the taper in Fig.(3.1) as a function of segment width for square and rounded rib-to-mesa interface transitions.

The rounded transition (inset) has a $0.25\text{ }\mu\text{m}$ radius curvature. The small oscillation in the calculation near $0.7\text{ }\mu\text{m}$ halfwidth is due to numerical instability.

Clearly, control of the etch depth to within $0.05\text{ }\mu\text{m}$ is required for fabrication of high-quality TRAFFiC spot-size transformers. *In-situ* reflectometry monitoring of etch depth is used^[22] to achieve the needed etch-depth control and reproducible mode-expansion efficiency. As a further aid in fabrication of TRAFFiC waveguides, the use of linear tapers with width variation in excess of the minimum required for spot-size transformation provides substantial tolerance to rib width, etch depth variations, and inaccuracies in

epitaxial layer composition and thickness. Non-linear tapers, with a rapid width variation in regions where the mode shape is relatively insensitive to rib width and much slower variation in the critical width region where the bulk of the mode transformation occurs, offer much shorter overall coupler lengths (and lower absorption losses) but also have significantly reduced processing tolerances for fabrication of low-loss couplers.

A common result of semiconductor rib waveguide etching is a rounded transition between the vertical rib sidewall and the horizontal mesa surface. Ribs with such a fillet behave within a TRAFFiC device as though the rib were square but slightly larger than the desired width. Figure 3.8 shows plots of the individual step coupling efficiency through the taper both with and without an actual $0.25\text{ }\mu\text{m}$ radius fillet at the bottom of the etched rib for the same etch depth used in Fig. (3.4). Addition of the radius to the rib reduces the halfwidth of the rib where spot-size transformation occurs by $\sim 0.1\text{ }\mu\text{m}$ and slightly improves the power conversion efficiency. The 1.5% improvement in efficiency is a direct result of the more gradual transition between the rib sidewall and mesa top.

Demonstration of coupler for high-efficiency *pin* modulators

The TRAFFiC structure discussed above is intended for use with high figure-of-merit *pin* phase modulators or Mach-Zehnder interferometers at $1.3\text{ }\mu\text{m}$ wavelength^[21,23]. Demonstration of coupler operation was done using discrete straight rib waveguides (Fig. 3.2a) and mesa waveguides (Fig. 3.2c) along with tapered rib waveguide structures on mesa waveguides (Fig. 3.2a-3.2c and Fig. 3.1b). These were fabricated using (Al)GaAs waveguides identical to Fig. (3.1a). The linearly-tapered waveguides used a $w = 0.7\text{ }\mu\text{m}$ final narrow width. Epitaxial layers were grown by molecular-beam epitaxy. The upper and lower cladding layers were doped p- and n-type, respectively, so that the $2.4\text{ }\mu\text{m}$ -wide rib waveguides are compatible with reverse-biased *pin*-junction phase modulators. Waveguide rib structures were patterned using electron-beam direct-write lithography with negative-acting electron-beam resist and a 25 nm exposed pixel spacing. Spacing between the 25 nm rib-width steps was approximately $15\text{ }\mu\text{m}$ for a 1 mm taper length. The mesa waveguide was patterned using conventional optical contact-print lithography. Etching of both the rib waveguide and mesa used chlorine reactive-ion-beam etching.^[22] Although these devices were patterned with direct-write techniques, the $0.7\text{ }\mu\text{m}$ minimum width of the waveguide taper could be defined using optical methods.

To evaluate mode spot-size transformation, a mesa waveguide and a tapered-rib mode converter were alternately excited using a single-mode fiber (3M, FS-HB-6621, design wavelength = $1.3\text{ }\mu\text{m}$ and modal field diameter = $7.1 \pm 0.2\text{ }\mu\text{m}$) emitting light at $1.31\text{ }\mu\text{m}$ wavelength. Near field images for the fiber, the mesa, and the tapered rib waveguide are shown in Figs. (3.9a)-(3.9c), respectively. Notice that the mesa guide and fiber are well matched and that the tapered rib output is very different. Unfortunately the limitations of the imaging optics result in the much smaller rib mode appearing relatively larger than its size

compared to the mesa and fiber modes. Power measurements demonstrate total mesa to rib waveguide coupling losses (excess loss) of $\sim 1.5 - 2.0$ dB and fiber to mesa coupling losses of ~ 0.5 to 1.0 dB. The larger than expected total mesa to rib waveguide coupling losses are understood by the unusually large straight waveguide propagation losses of 9.2 ± 0.8 dB/cm exhibited by both the straight rib and mesa waveguides on this sample.

Figure 9

Figure 3.9: Experimental results showing near-field images of the: a) light exiting the optical fiber b) light coupled from a fiber and traveling through a mesa waveguide without a taper, and c) light coupled from a fiber to a mesa waveguide then traveling through a Tapered-Rib Adiabatic-Following Fiber Coupler and exiting from a rib waveguide. Fig. 3.9(c) demonstrates the desired spot size transformation. Each of the three images is accompanied with a schematic representation of the configuration used to obtain the image.

Design and demonstration of 980 nm laser with expanded mode output

An InAlGaAs diode laser with a TRAFFiC output was demonstrated at 980 nm wavelength. Such expanded-mode semiconductor lasers^[19,20] are of great interest due to the benefits of reduced far-field divergence and improved coupling efficiency to single-mode optical fiber. The TRAFFiC laser description (Fig. 3.10) follows closely that of the previous discussion and comprises a uniform 2 μm -wide AlGaAs/InGaAs heterostructure gain section and TRAFFiC waveguide mode converter tapered down to a 0.7 μm final width. Using a procedure identical to that described above for the 1.3 μm wavelength *pin* waveguide, overall power-conversion efficiency of the mode expansion is estimated to be 90%. The expanded mode supported by the mesa guide has a simulated coupling efficiency to single-mode fiber of greater than 95%.

Figure 3.10: Representation of the TRAFFiC laser showing the tapered-rib upper cladding shape and the approximate form and size of the optical mode in the active gain section in the wide rib region (inset) and the expanded size and shape of the output optical mode at the cleaved end where the rib is most narrow.

The laser is a strained-quantum-well separate-confinement heterostructure type described in Table (3.1). A 2 μm -wide rib waveguide is etched in the cladding region above the quantum wells to define the active lasing section in a region of high vertical confinement factor. A TRAFFiC output coupler section is inserted between the active waveguide and one of the cleaved facets by tapering the rib waveguide width from 2 μm to 0.7 μm over a length of 1.0 mm. A second 10 μm -wide outer mesa provides lateral confinement of the expanded optical mode propagating within the thick lower cladding. The low 10% Al content of the cladding material prevents formation of modes guided by the remaining GaAs material at the top of the mesa and subsequent failure of the mode expansion. Overall length of the lasers is 1.5 mm of which 1 mm is contacted for electrical current injection. The TRAFFiC section is electrically injected only in the first half of the coupler where significant overlap of the optical mode and InGaAs quantum wells exists.

Table 3.1: Epitaxial structure of TRAFFiC laser for 980 nm operation. (Resonant periodic marker layers¹⁵ used for *in-situ* monitoring of the etches but having virtually no impact on device performance have been omitted for clarity.)

Material	Thickness (nm)	Doping (cm^{-3})	Description
GaAs	100	$p = 8\text{e}19$	Cap Layer
$\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$	500	$p = 2\text{e}18$	Upper Cladding
$\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$	1500	$p = 5\text{e}17$	Upper Cladding
grade from	90	uid	Graded Interface
GaAs	60	uid	Active Waveguide
$\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$	8	uid	Quantum Well
GaAs	15	uid	Barrier
$\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$	8	uid	Quantum Well
GaAs	60	uid	Active Waveguide
grade to	100	uid	Graded Interface
$\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$	2000	$n = 5\text{e}17$	Mesa Waveguide
$\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$	5000	$n = 1\text{e}18$	Mesa Waveguide
$\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$	1000	$n = 2\text{e}18$	Mesa Waveguide
$\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$	1000	$n = 3\text{e}18$	Waveguide Barrier
GaAs	substrate	n^+	

Lasers were fabricated in MOCVD-grown material using two lithography-and-etch steps. The tapered rib waveguide was defined using electron-beam direct-write lithography. The wide mesa was patterned using optical contact printing. Both were etched using non-selective Cl_2 dry etching. After etching, the surface was coated with plasma deposited SiO_2 , a window opened on top of the rib for p-side ohmic metalization and BeAu ohmic contacts formed. The backside of the wafer was coated with AuGeNiAu ohmic contact metalization prior to rapid-thermal annealing at 360°C . Figure 3.11 shows an SEM image of a completed TRAFFiC laser. As experimental control devices, uniform 2 μm wide lasers were also fabricated on the same wafer as the TRAFFiC lasers. Final lasers were tested as-cleaved

without facet coatings or heatsink. Injection current was pulsed using 2 μ s pulses at a 1 kHz repetition rate. Fig. (3.12) shows the light output characteristic of a TRAFFiC laser and a 2- μ m wide by 1.25 mm-long control device. Although slope efficiencies are comparable, threshold current of the TRAFFiC laser is 110 mA compared to 81 mA for the control. In addition, a kink is seen at approximately 150mA injection current in the TRAFFiC laser output which is not seen in the control device output. This behavior may be due to non-ideal current injection in the taper section. Only a portion of the taper is contacted for current injection as shown in Fig. (3.11). Current injection into the taper stops at a point approximately midway along the length where the width of the rib becomes too small to open a contact window in the dielectric cap using conventional contact lithography. As a result light confined in the quantum wells below the un-contacted taper region will experience higher absorption. This higher absorption increases the lasing threshold current and reduces efficiency. However, as the current injection increases the quantum well refractive index will decrease in the contacted regions of the rib causing the mode to move into the mesa at relatively larger rib widths. Therefore, at higher injection levels the overall absorption loss of the taper will decrease resulting in an increase in laser efficiency. The kink at $\sim$ 150mA injection current is consistent with increased laser efficiency resulting from reduced taper losses. More uniform current injection using optimized layer doping, taper length, processing and electrical contacting are expected to give reduced lasing threshold compared to these demonstration devices.

Figure 3.11: SEM image of TRAFFiC laser mode-expansion section. Metalization on gain section is seen at the top of the image. Passive rib and mesa comprising the TRAFFiC 2D mode-expander are seen extending between the metal and the cleaved output facet.

Figure 3.12: Threshold characteristics of TRAFFiC and 2- μ m wide control lasers. Data is for 2 μ s pulses at 1 kHz repetition rate.

Coupling efficiency of the TRAFFiC output to optical fiber was measured using a 1 m length of Spectran SMB-E1310B fiber (this fiber is single mode above 1.25 μ m wavelength and has an NA = 0.17 at $\lambda = 1.3$ μ m.) butt-coupled to the laser facet. The fiber ends were as-cleaved without polishing or lensing of any kind and the bulk of the fiber length was wrapped around a 9cm diameter spool. TRAFFiC laser output including transmission into and through the length of single-mode fiber is shown as the lower curve in Fig. (3.12). Measured coupling loss from the laser into the fiber is only 0.9 dB.

The far-field optical emission pattern was measured using a 25 mm-long Si CCD array placed 38 mm from the facet. Fig. (3.13) shows the far-field intensity pattern of two representative TRAFFiC lasers both perpendicular and parallel to the plane of the epitaxial layers. The far-field patterns are quite stable over a wide range of injection current. The solid line of Fig. (3.13) is the 1D far-field calculation^[24] based on 2D numerical simulations

of the TRAFFiC output. Excellent correlation between the observed and theoretical patterns is observed. The 5.6° and 7.4° full-width-half-maximum (FWHM) far-fields in the perpendicular and parallel axes respectively are significantly smaller and more symmetric than the $\sim 35^\circ$ and $\sim 9^\circ$ FWHM values commonly seen in conventional double-heterostructure AlGaAs lasers.

Near-field image measurements of both a TRAFFiC laser and a $2\text{ }\mu\text{m}$ -wide control laser are shown in Fig. (3.14). The TRAFFiC laser is clearly seen to have a much larger fundamental optical mode as compared to the control device. As seen schematically in Fig. (3.10) and in the measured profile of Fig. (3.14b), the output mode is intended to be roughly as tall as it is wide with a characteristic inverted mushroom shape. Back facet emission image of the TRAFFiC laser is indistinguishable from that of the control laser, Fig. (3.14a). No evidence of high-order modes is seen at any tested current level.

Figure 3.13: Far-field emission patterns of TRAFFiC laser output along axes parallel (a) and perpendicular (b) to the epitaxial layers. Symbols are measured data from two different lasers. Solid line is simulation result.

Figure 3.14: Linearly-spaced contour plots of measured near-field emission intensity pattern of (a) 2- μm -wide control laser, and (b) expanded-mode TRAFFiC laser.

Summary

In summary, we have designed and demonstrated a monolithic tapered rib waveguide for spot-size transformation. The TRAFFiC device achieves 2D expansion of the output optical mode of single-transverse-mode semiconductor waveguide modulators and lasers using a 1D taper between non-critical initial and final taper widths which are compatible with optical lithographic techniques. Design details for (Al,Ga)As TRAFFiC waveguides have been given and effects of taper width, step size, etch depth and etch profile simulated. Using the TRAFFiC device, total mode expansion losses of $\sim 1.5 - 2.0$ dB and semiconductor to fiber waveguide coupling losses of ~ 0.5 to 1.0 dB have been measured for doped *pin* optical-modulator-type waveguides at $1.32\mu\text{m}$ wavelength. A TRAFFiC mode-expansion section has been integrated with a 980 nm rib-waveguide diode laser and stable fundamental mode operation with a narrow, 5.6° by 7.4° FWHM far-field observed well above lasing threshold. The observed mode size and far-field divergence are consistent with numerical simulation of the TRAFFiC laser structure and measured coupling loss from the TRAFFiC laser output to single-mode, long-wavelength telecommunications fiber is only 0.9 dB. All of these mode-expansion waveguides are fabricated using a single epitaxial growth followed by two lithography-and-etch procedures and use dimensions compatible with conventional photolithographic techniques.

The TRAFFiC structure is particularly well suited for integration with both active and passive etched rib waveguide devices. Fabrication is relatively simple, requiring only patterning and etch of the tapered waveguide and uniform-width outer mesa waveguide without any epitaxial regrowth.

With a fully-developed TRAFFiC laser, a $4\text{-}\mu\text{m}$ -wide rib waveguide is placed between *two* TRAFFiC structures at the cleaved output facets. The resulting laser combines the attributes of a moderately confining, narrow, rib (low threshold current and stable fundamental mode operation) with the benefits of a large output mode size (reduced beam divergence and lower peak intensity at a given output power.) Maximum output power will be limited to roughly 450 mW due to the narrow rib and high Γ value. This maximum power is one-fourth COD limit of the $8\text{ }\mu\text{m}$ by $10\text{ }\mu\text{m}$ output facet. Under gain-switched operation the TRAFFiC laser may be capable of several watts peak pulse power with a narrow, symmetric, far field divergence of $\sim 7^\circ$ FWHM.

Large optical cavity lasers for high pulsed power

As described in the previous section, the TRAFFiC laser is limited in output power by gain saturation in the narrow rib. An attractive concept to eliminate this limitation is to build a very large optical cavity (VLOC) laser wherein the laser is longitudinally invariant and the optical mode remains as large as the output mode of the TRAFFiC laser.

The VLOC laser was expected to achieve record output powers by means of lowering the confinement factor of the optical mode within the active material. Since I_S is fixed by fundamental properties of the quantum well, total power output can be increased by creating a much larger optical mode having the same peak intensity, I_S . We pursued this using an $\sim 8\text{ }\mu\text{m}$ -thick AlGaAs layer over a relatively thin AlGaAs layer of lower refractive index. When patterned into a $4\text{ }\mu\text{m}$ tall by $10\text{ }\mu\text{m}$ wide rib, these two AlGaAs layers form an optical waveguide with an $8\text{ }\mu\text{m}$ by $10\text{ }\mu\text{m}$ mode size, significantly larger than the conventional $1.5\text{ }\mu\text{m}$ by $10\text{ }\mu\text{m}$ mode. An MQW gain region is placed in the center of this waveguide provided that the overall refractive index perturbation is zero. The resulting laser has a gain confinement factor of only 0.007 and an expected output power limit 10 W for 1 to 100 ns pulses. The COD limit of such a large optical mode should occur between 2.5 and 10 W. The key technological hurdle of the VLOC laser compared to conventional diode lasers, as well as previous LOC lasers, is the creation of an active region which does not perturb the optical mode significantly compared to the same waveguide layers without an active region. This allows for a larger mode and smaller confinement factor compared to previous work. Under gain-switched operation the VLOC laser may be capable of much more than 10 watts peak pulse power in the sub-ns regime with a narrow, symmetric, far field divergence of $\sim 7^\circ$ FWHM.

Figure 4.1: Illustration of TRAFFiC (left) and VLOC (right) high-power edge-emitting laser designs. Tapered narrow waveguide rib is evident on top of the TRAFFiC mesa. In the VLOC design the large mode is invariant throughout the length of the laser.

The power/performance payoff made exploration of VLOC lasers very attractive in spite of the technical difficulty of actually building such a large active waveguide with *no* index perturbations. The risks involved in using the VLOC structure is that small perturbations of

the index can cause the optical mode to become guided or anti-guided by the gain layers. Both effects tend to reduce mode size and output power. To minimize these effects, numerical simulation of the VLOC waveguide was used to determine the influence of material gain, impurity doping, and resistive temperature changes on mode quality. Since gain is a function of injection current, the VLOC laser was not expected to exhibit an optimum mode shape at all injection currents. However, waveguide structures were designed which compensate for the effects of gain and temperature at high injection levels (gain is clamped to a nearly constant value well above threshold) so as to optimize the mode shape at high output power.

A number of design iterations were tried. This report will discuss one of these so as to give a good idea of the difficulty of the task and the results obtained.

Waveguide Design with Thermal and Gain Compensation

A VLOC design is shown in Fig. 4.2. A series of epitaxial layers are shown as the regions bounded by horizontal straight lines. The fundamental optical mode is seen as a series of contour lines of constant optical field. This particular model uses a gain of 1000 cm^{-1} in the MQW region (thick line in figure) but sets the entire structure at room temperature.

Figure 4.2: Simulation of VLOC device at room temperature.

Figure 4.3: Simulation of temperature modulation of VLOC laser with 580 mA current injection.

Figure 4.4: Simulation of final optical mode including effects of gain and heating. The optical mode is pulled up into the rib by the temperature profile effects on the local refractive index.

Resistive heating is a significant perturbation on the material refractive index. Effects of heating caused by a 580 mA forward bias injection current were simulated numerically as shown in Fig. 4.3. Note that the temperature rise in the rib area is much greater than the unetched area below the MQWs. This is a direct effect of the higher current density in the narrow rib. The result of this uneven temperature rise is a similarly uneven increase in the local refractive index (not shown).

The optical mode of the VLOC laser with temperature effects is shown in Fig. 4.4. Note that the final mode is pulled up into the rib and straddles the MQW region more effectively than does the simulated mode without heating. This reflects a built-in material asymmetry used to set-up the laser for optimal operation including the effects of gain and heating.

VLOC laser test results

Lasers were tested with 200 ns pulses at 10 KHz repetition rate. Figure 4.5 show the light output characteristic of a VLOC laser. Lasing threshold is achieved at 450 mA drive current. Maximum power output is 190 mW at 1.4 A. COD is seen at higher drive currents. This premature onset of COD suggests that the mode size is not as large as needed for successful operation of the laser. Figure 4.6 show measurement of the optical mode. At low power levels, Fig. 4.6(a), the mode is well behaved and looks like the predicted mode of the simulation in Fig. 4.4. However, at higher drive currents, higher-order optical modes dominate, such as the TE_{11} -like mode shown in Fig. 4.6(b). Such high-order modes have a much larger power density at the cleaved facet resulting in the observed premature onset of COD. This mode instability has prevented operation of VLOC lasers at the gain saturation limit.

Figure 4.5: Light output versus drive current of a VLOC laser.

(a)

(b)

Figure 4.6: False color near-field emission images of VLOC lasers. (a) Low power operation of 1 mW or so shows the large mode size desired for high-power use. (b) High-power operation, about 100 mW, shows that the mode has become dominated by TE_{11} -like operation.

Conclusions

We have been very successful in the development of gain switched flared laser diodes with 1 nJ or better pulse energy. Such pulse energies are the threshold value above which remote sensing applications become feasible. During the course of this LDRD program we ultimately achieved 17 W peak power with 1.4 nJ pulse energy. These energy levels are world record values for QW laser diodes. Adiabatic mode expanders with applications in high power laser diodes have been developed. These mode expanders raise the COD limit of the laser by reducing the power density at the laser facet. Diode lasers with integrated mode expanders have been demonstrated and do show very well behaved modal properties. Attempts were made to fabricate diode lasers with very large mode size as a means to reduce the power density throughout the laser diode. These lasers have so far proved disappointing due to modal instability of the waveguide.

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