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Broadband 2.4 μm superluminescent GaInAsSb/AlGaAsSb quantum well diodes for optical sensing of biomolecules

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Abstract

High power, high radiance, broadband light sources emitting in the 2.0-2.5 μm wavelength range are important for optical sensing of biomolecules such as glucose in aqueous solutions. Here we demonstrate and analyze superluminescent diodes with output centered at 2.4 μm (range ~2.2-2.5 μm) from GaInAsSb/AlGaAsSb quantum wells in a separate confinement structure. Pulsed wave output of 1 mW (38 kW/cm²/sr) is achieved at room temperature for 40 μm $\times$ 2mm devices. Superluminescence is evidenced in superlinear increase in emission, spectral narrowing, and angular narrowing of light output with increasing current injection. Optical output is analyzed and modeled with rate equations. Potential routes for future improvements are explored, such as additional Auger suppression and photonic mode engineering.

Keywords

GaInAsSb; GaSb; gallium antimonide; light emitting diode; superluminescence; glucose sensing; optical chemical sensing; high power; infrared; combination region

1. Introduction

Superluminescent diodes (SLD) emitting in the short-wave infrared are of interest for high power, broadband light sources for compact, optical point-sensing of molecules. The 2-2.5 μm range, or “combination region,” is of particular interest for chemical sensing of biomolecules in aqueous solutions, where broad, overlapping characteristic absorption resonances exist for a variety of biomolecules, such as glucose, lactate, urea, and triacetin, due to vibrational stretching and bending of C-H, O-H, and N-H bonds, and a water absorption minimum.^{1,2} It has been shown that selectivity of a composite solution of biomolecules can be achieved using multivariate techniques, such as partial least squares regression. Such an approach requires an absorption measurement across the 2-2.5 μm spectral region to achieve selectivity.

Note absorption resonances of biomolecules in aqueous solutions are much broader than gas molecules. Hence traditional strategies for gas sensing using lasers tuned over several nanometers by e.g. temperature tuning are not useful in this context. High power, laser diodes can achieve broader tuning by utilizing external cavities, and GaInAsSb/AlGaAsSb quantum well lasers have demonstrated tuning over a portion of the combination region, 2.21-2.33 μm .^{3,4} External cavity tunable lasers may make sense for biomolecule monitoring in controlled settings such as the laboratory or hospitals, but are bulky and require moving parts so are not suitable for compact, low cost point sensors for more rugged conditions. In contrast, it has been shown that room temperature mesa surface light-emitting diodes from GaInAsSb/GaSb emit over the full 2-2.5 μm wavelength region. These emitters have reported upper hemisphere powers of 300 μW ⁵ (0.9 mW)⁶ continuous wave at room temperature for 200 μm (300 μm) diameter mesas. They have been incorporated into point glucose sensors,⁷ and which were able to detect glucose in bovine blood ultrafiltrate with 2 mM standard error of prediction, too high for clinical relevance, but an important demonstration of principle.

To improve the signal-to-noise ratio, we investigate superluminescent, edge-, light-emitting diodes from GaInAsSb/AlGaAsSb quantum well heterostructures, which have the potential for higher output powers and radiances because they utilize amplified spontaneous emission, yet remain broadband by avoiding laser oscillation.

SLDs employ heterostructures similar to laser diodes, and are fabricated as ridge waveguides for edge emission like laser diodes. However, unlike laser diodes, SLDs seek to operate below threshold to maintain a broad emission spectrum. To achieve high output powers without lasing, the threshold for lasing is raised by reducing feedback into the cavity using various approaches including an absorbing facet,⁸ angled facets,⁹ anti-reflection coating the facets, bending the waveguide¹⁰, using a tapered waveguide,¹¹ or using some combination of these approaches.^{12,13} Previous investigations of SLDs have focused on materials for communication wavelengths (800-900 nm, and 1.3 to 1.5 μm) such as GaAs/AlGaAs,^{8,9} GaInAsP/InP quantum wells,^{13,14} and InAs/GaAs quantum dots^{15,16}, which output tens to hundreds of mWs of power at room temperature, as well as one report on a 6-8 μm quantum cascade SLD, which output tens of μW at low temperature.¹⁷ Here we report on the performance of GaInAsSb/AlGaAsSb quantum well heterostructure SLD operating in the 2-2.5 μm wavelength range at room temperature using simple straight ridge waveguides with angled facets. We simulate the characteristics both to analyze the device limitations, and to point the way to future improvements.

2. Experimental and Theoretical Methods

2.1 Growth

A schematic of the heterostructure grown for this study is shown in Fig. 1. The design was based on a report of high power, 2.0-2.5 μm GaInAsSb/AlGaAsSb quantum well, separate confinement heterostructure diode lasers using a novel waveguide design to reduce beam divergence.^{18,19} Our quantum wells consisted of a quaternary alloy estimated to be $\text{Ga}_{0.58}\text{In}_{0.42}\text{As}_{0.14}\text{Sb}_{0.86}$ based on calibrated growth rates of the group-III-limited growth, and fits to high-resolution x-ray diffraction (HRXRD) scans. Barriers consisted of the alloy

$\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}_{0.02}\text{Sb}_{0.98}$, which is lattice-matched to the GaSb substrate. For quantum wells of this composition, the 1.7% strain in the quantum wells has been determined to adequately confine holes.

Samples were grown in an Applied Epi EPI930 molecular beam epitaxy (MBE) chamber employing (Mark IV) valved crackers for the group V sources, and dual filament SUMO cells for group III sources. The $\text{Ga}_{0.58}\text{In}_{0.42}\text{As}_{0.14}\text{Sb}_{0.86}$ quantum well alloy is not trivial to grow, both because the alloy is thermodynamically unstable at the temperatures at which it was grown, and the high compressive strain of 1.7% makes the layer prone to relaxation. However, these materials have been used in a number of successful laser diodes, as well, though the degree of phase separation and relaxation was not examined in those cases.^{20,21} It has been shown that metastable and unstable GaInAsSb quaternary alloys can be grown under non-equilibrium conditions in MBE by employing low growth temperatures to limit adatom diffusion, and strain to suppress phase separation and improve material quality.^{22,23} Figure 2(a) shows an optical interferometric image (Wyko NT1100 optical profiling system, 2 nm vertical resolution) of the surface of a bare quantum well sample consisting of one 14 nm/ 20 nm $\text{Ga}_{0.58}\text{In}_{0.42}\text{As}_{0.14}\text{Sb}_{0.86}$ / $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}_{0.02}\text{Sb}_{0.98}$ quantum well with 100 nm $\text{Al}_{0.50}\text{Ga}_{0.50}\text{As}_{0.04}\text{Sb}_{0.96}$ clads plus a 5 nm GaSb cap grown at 450 C. The surface has a smooth surface with a low density of small defects. If the growth temperature was increased to 475 C, the density of the small defects increased approximately 100 fold. Growth temperatures were determined with an optical pyrometer calibrated to a GaSb RHEED transition at 410 C.²⁴

Parameters for lattice matching $\text{Al}_{0.50}\text{Ga}_{0.50}\text{As}_{0.04}\text{Sb}_{0.96}$ and $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}_{0.02}\text{Sb}_{0.98}$ were determined in separate growths. The bottom Al containing quaternary layers were grown at 520 C; after the sample was cooled to 450 C for the quantum well growth, it was not reheated for the top Al containing quaternary cladding layers to avoid degrading the quantum well. Because only a single Al and Ga cell was used, graded regions between the 25% buffer and 50% Al quaternary layers were achieved by stepping the alloys linearly in 10 nm, 5% Al steps, and with 60 second pause between steps to ramp cell temperatures. All layers in the structure were grown with true group V/III ratios between 1 and 2, where true V/III ratio is calculated by normalizing BEP V/III ratios by the minimum BEP V/III ratio needed to achieve group III limited growth rates.

Figure 2(b) shows a high resolution x-ray diffraction measurement of the complete heterostructure shown in Fig. 1, and comparison to simulation of the whole structure assuming coherent strain. The good agreement shows the excellent overall structural quality of the sample.

2.2 Fabrication

Samples were wet etched in two runs with an etchant consisting of citric acid, phosphoric acid, and hydrogen peroxide. The cathode etch was to the n-GaSb buffer layer; and the channel etch, which defined the lateral waveguide, was only about 1 μm deep and not through the active region. Waveguides were then blanketed with polyimide to passivate the sidewalls, and a window was opened along the ridge for the anode contact. Both contacts were established in a single run through e-beam evaporation of Ti/Pt/Au. The n-contact was

enlarged to reduce contact resistance. Waveguides were 40 μm wide, and were cleaved to different lengths between 0.8-2.7 mm by using a diamond tip scribe outside the waveguide, then pulling the chip apart with a pair of forceps. Samples were flip-chipped and pressure bonded to indium contacts on Si/SiO₂ headers. The purpose of different waveguide lengths in laser diodes was to extract waveguide loss from the dependence of inverse differential efficiency on waveguide length as discussed further below. SLD's were cleaved to 2 mm, as longer waveguides are desired for greater amplification.

Waveguides were either oriented parallel to the $\langle 010 \rangle$ crystal axes to give facets normal to the waveguide and 33% reflection for Fabry-Perot laser diode devices; or they were oriented at a 8° angle to $\langle 010 \rangle$ to give angled facets. Angled facets have been shown to greatly reduce facet reflection. Experimental values of facet reflection in similar GaAs/AlGaAs waveguides with cleaved facets smoothed with focused ion beam milling were previously obtained,²⁵ with a reflection reduced from 33 at normal incidence to as low as 2×10^{-3} for the same 8° angled facets as used here. However, facets here are likely higher than that, because the softer GaInAsSb/AlGaAsSb used here makes clean cleaves more difficult, and no focused ion beam smoothing was employed.

2.3 Measurements

Power versus current and voltage (LIV) data was measured by integrating device output under quasi-cw conditions over a 0.66 sr solid angle using f/1 parabolic mirrors. Samples were mounted on a copper heat sink with indium foil between copper and header. Current was injected in 200 μs square pulses at varying currents and low duty cycles (1-5%). Power was measured with a calibrated room temperature extended-wavelength InGaAs detector. Data was taken at room temperature (295 K) with no active cooling or temperature stabilization, and no degradation was observed when comparing 1% and 5% duty cycles. Emission spectra were measured using a Nicolet 560 FTIR spectrometer using a double signal modulation approach in combination with an LN₂ cooled InSb detector.⁵

2.4 Modeling

Modeling of LI data was done by numerically solving rate equations ((1)-(5) below)²⁶ at equilibrium for carrier density n and cavity photon density S for input current density J .

$$\frac{dn}{dt} = \frac{J}{ed} - G(n)S - \frac{n}{\tau_n} \quad (1)$$

$$\frac{dS}{dt} = G(n)S - \frac{S}{\tau_{ph}} + \beta_{sp} \frac{n}{\tau_r} \quad (2)$$

$$G(n) = \Gamma g_0 (n - n_0) \quad (3)$$

$$\frac{1}{\tau_n} = A + Bn + Cn^2 \quad (4)$$

$$\frac{1}{\tau_{ph}} = \frac{c}{n_r} \left(\alpha_i + \frac{1}{2L} \ln(R^{-2}) \right) \quad (5)$$

Here $G(n)$ is the amplification rate of the SLD, Γ is the optical confinement factor, and g_0 the differential gain coefficient; n_{th} is the threshold current density for lasing, and n_0 is the transparency carrier density; τ_n is the total carrier lifetime, τ_{ph} is the photon lifetime in the cavity, and τ_r is the radiative lifetime ($B=n/\tau_r$); A , B , and C are Shockley-Read-Hall, radiative, and Auger coefficients, respectively; n_i is the effective index of refraction of the waveguide stack, α_i is the waveguide loss coefficient, and L is the length of the gain region (i.e. = waveguide length); and β_{sp} is the fraction of spontaneously emitted light into the waveguide modes.

We solved for $n(J)$, $S(J)$, and output power as a function of current density ($P(J)$) as follows. First, (1) and (2) were set to zero for steady state, (2) was solved for $S(n)$ and substituted into (1) to yield:

$$0 = \frac{J}{ed} - G(n) \frac{\beta_{sp} n}{\tau_r} \frac{1}{(\tau_{ph-sld} - G(n))} - \frac{n}{\tau_n} \quad (6)$$

$$S(n) = \frac{\beta_{sp} n}{\tau_r} \frac{1}{(\tau_{ph-sld} - G(n))} \quad (7)$$

Here we have written the SLD photon cavity lifetime τ_{ph-sld} to emphasize that this constant is distinct from that of the laser diode cavity due to different facet reflectivity. The strategy is to solve (1) numerically for $n(J)$, then use $n(J)$ in (7) to calculate $S(J)$. Once $S(J)$ is known, the output power of the SLD $P(J)$ can be calculated using:

$$P = \frac{SVhv}{\tau_{ph-sld}} \quad (8)$$

where V is the cavity volume.

Before solving (6) and (7) for $n(J)$ and $S(J)$, we needed an expression for $G(n)$, the amplification factor. We assumed this factor was the same for the SLD and the laser, and took advantage of the fact that for the laser,

$$G(n) = \frac{n - n_0}{\tau_{ph-laser} (n_{th} - n_0)} \quad (9)$$

so that $G(n) = 1/\tau_{ph-laser}$ above threshold. Note comparison of (3) and (9) give:

$$\Gamma g_0 = \frac{1}{\tau_{ph-laser} (n_{th} - n_0)} \quad (10)$$

$\tau_{ph-laser}$ can be calculated from (5) if waveguide loss is known, the estimate of which is discussed in the next paragraph, as well as laser diode facet reflection, which is straightforward to calculate from effective index and Fresnel equations. τ_{ph-sld} can be

similarly calculated using the same waveguide loss, and reduced reflection of the angled waveguide facet. n_{th} is also straightforward to calculate: $n_{th} = \frac{\tau_n J_{th}}{eL}$, where e is electron charge, and J_{th} is the threshold current density. We used $J_{th} = 300 \text{ A/cm}^2$, a typical low threshold current and a bit higher than the 250 A/cm^2 in Fig. 3, and corresponding $n_{th} = 1.21 \times 10^{19} \text{ cm}^{-3}$. τ_n can be calculated from (4). For A, B, and C coefficients, we used: $A = (1.3 \times 10^{-7} \text{ s})^{-1}$ $B = 5 \times 10^{-11} \text{ cm}^3/\text{s}$ $C = 2 \times 10^{-28} \text{ cm}^6/\text{s}$.²⁷ We had no clear way to estimate n_0 , so it was treated as a fit parameter. For the simulations presented here, we used $n_0 = 0.88 n_{th}$.

To calculate waveguide loss, straight laser diode waveguides of different lengths L were fabricated from the epitaxial wafer. For each variable laser diode, the differential quantum efficiency above J_{th} was extracted from the slope of power versus current: $\eta_d = \frac{e}{h\nu} \frac{dP}{dI}$, where I is current, and h is Planck's constant. Because we can write

$$\frac{1}{\eta_d} = \frac{\alpha_i L}{\eta_i \ln\left(\frac{1}{R}\right)} + \frac{1}{\eta_i} \quad (11)$$

where η_i is the fraction of current reaching the active region, a plot of $1/\eta_i$ versus diode length L gives η_i from the y-intercept, and α_i from the slope. Such a plot is shown in Fig. 4, with 5 cm^{-1} being our best estimate of α_i .

3. Results and Discussion

The angled waveguides fabricated in this study clearly exhibit superluminescence. Whereas the gain in a laser clamps with increasing current injection after the onset of lasing, gain in the SLD continues to grow; the exponential amplification of spontaneous emission along the waveguide therefore has the potential to grow superlinearly with increasing current. We illustrate this behavior in a later section with theoretical simulations. Figure 5, which is a plot of light out and voltage versus current density (LIV), shows the range of behaviors observed by the edge emitting, angled waveguide structures. Chip 1 exhibits the expected superlinear growth in the output power with increasing current, evidence of superluminescent output.

Unlike the spectrally narrow emission of a laser, the output of a SLD should remain broadband, because it does not have the feedback characteristic of a Fabry-Perot laser. Figure 6 shows that the spectrally resolved output of Chip 1 is broad, with a $1/e$ full width of 230 nm (83 meV) at low current densities, consistent with the typical width of several $k_B T_{\text{room}}$ ($\approx 25 \text{ meV}$) of emission of a thermalized population of carriers recombining through spontaneous emission. However, with increasing gain, the superluminescent output is expected to narrow slightly due to the wavelength dependence of the gain coefficient, because wavelengths near the center of the emission experience greater gain than wavelengths away from the peak. Figure 6 shows clear spectral narrowing of the output with increasing current injection.

Chip 2 also shows evidence of superluminescence. Superlinear growth in Fig. 5, however, was weak. Spectral narrowing is evidenced in Fig. 7, but is also accompanied by a blue shift of the emission, indicative of band filling. It is likely this device suffered from either

increased waveguide loss, as observed in Fig. 4; or increased heating due to higher contact resistance, or perhaps increased nonradiative recombination from roughened facets.

Finally, superluminescence might be expected to lead to a redistribution in the angular output of the edge emission. Figure 8 shows how the angular distribution of the emission from the end of the waveguide along the slow axis becomes increasingly weighted in the forward direction compared to high angles, with the angular full width at half maximum decreasing by almost a factor of two from 32.5° to 17.5° . Such behavior is expected as amplified spontaneous emission from along the waveguide modes grows and dominates spontaneous emission in all directions, and is further evidence of superluminescent action of the diode.

Chip 3 exhibited lasing action rather than superluminescence. In Fig. 6, it shows threshold-like behavior; and in Fig. 9, it shows narrow spectral emission (1 meV for all modes, less than 0.1 meV for individual modes) characteristic of a laser. Examination of the facets showed significant damage at one facet that likely led to increased feedback, lowering the threshold for lasing. Chips 2 and 3 highlight the challenge we experienced in obtaining reliably smooth facets from the softer antimonide materials compared to wider gap semiconductors, as well as the potential consequences of rough facets.

Figure 10 characterizes the efficiency of Chip 1, the device exhibiting strong superluminescence.

Plotted are wallplug efficiency, $\frac{P_{out-1-facet}}{VI_{in}}$; quantum efficiency, $\frac{P_{out-1-facet}/E_{photon}}{I_{in}/e}$; and differential quantum efficiency (η defined earlier). Note P only counts photons emitted out of one facet of the device, not output in all directions. The wallplug efficiency begins at about 2%, drops sharply at first, then begins to level off, while the quantum efficiency and differential quantum efficiency increase sharply with increasing current as the output grows superlinearly. At high current densities, all three efficiencies approach a few tenths of a percent.

The differential quantum efficiency approaches a half percent at peak, a factor of twenty to fifty times lower than that of our straight waveguide lasers (see Fig. 4). The lower efficiency is due to the greater cavity losses as a result of reduced facet reflection, and to greater nonradiative (Auger) scattering operate at (see below). The rollover in differential and quantum efficiency at the highest current densities may be due to heating: Chip 1 output showed a slight dependence on the duty cycle as it was increased from one to five percent (not shown). The rollover may also be due to reduced carrier confinement, particularly of holes.²⁸

Our theoretical simulation of superluminescence is able to qualitatively reproduce the observed features of superluminescence for the L-J curve. Figure 11 shows comparison of simulated output using the theory discussed in Sec. IID, and the measured output of Chip 1. The simulation shows that the superlinear growth in output is expected to occur as the active region transparency is crossed (at about 220 A/cm^2), knees upward as gain grows and the chip approaches the lasing threshold, which occurs in angled waveguides when the

amplification rate $G(n)$ equals the cavity lifetime of a photon in the angled waveguide ($\tau_{\text{ph-sld}}$).

Figure 12 shows the corresponding carrier density in the simulated superluminescent device output in Fig. 11. Also shown is the threshold carrier density for a straight waveguide laser diode with an identical heterostructure, as in Fig. 3. Figure 12 shows that carrier density in a SLD does not clamp like a laser diode, but keeps increasing with current density. Losses to nonradiative (Auger) recombination will become increasingly problematic as the superluminescent output and carrier density get very high.

To point the way to future improvements in these superluminescent devices, we theoretically examined the sensitivity of the output to several engineerable parameters, including facet reflection R , fraction of spontaneous emission into the waveguide mode β_{sp} , and the Auger nonradiative scattering coefficient C . Each of these parameters can be engineered over orders of magnitude,^{27,29} but we just look at factor of ten changes in order to look at relative trends. The results are shown in Fig. 13. If R is decreased by $\times 10$, then feedback into the cavity is reduced, the lasing threshold is raised, and device output becomes less efficient as cavity losses increase. On the other hand, higher current densities can be accessed without lasing, and at these higher current densities, the gain spectrum will be broader leading to less spectral narrowing. Reducing the R of the facets lower than what is achievable with an angled waveguide might be done by antireflection coating facets in addition to angling them.

If the Auger coefficient could be engineered to be $10\times$ lower, the device output and quantum efficiency improve by about $5\times$, which is not surprising given the very high current densities that these devices operate at, while the threshold is nearly unchanged. The Auger coefficient is expected to be suppressed in quantum wells as compared to bulk due to the reduction in the valence band density of states caused by strain and quantum confinement.²⁹

Finally, if β_{sp} is increased by $\times 10$, the output of the SLD increases by about a factor of $\times 10$ without changing the threshold significantly. Given that β_{sp} is already very low, about 10^{-4} , an increase of $\times 10$ seems plausible. β_{sp} could potentially be increased by fabrication of a photonic crystal waveguide, suppressing spontaneous emission losses out of the waveguide.

4. Conclusions

We have observed superluminescent output in angled waveguide, GaInAsSb/AlGaAsSb strained quantum well heterostructures emitting at $2.4\ \mu\text{m}$. The superluminescence is evidenced by the superlinear growth in output power, and the spectral and angular narrowing with increasing current. Output powers up to $1\ \text{mW}$ into an $F/1$ solid angle were observed at room temperature and pulsed conditions from end facets of area only $40\times 5\ \mu\text{m}^2$.

Comparing the results here to trends in other SLDs in the visible and long-wave infrared, discussed in the introduction, we see a significant drop off on output power with increasing wavelength. This overall trend is due to the rapid increase in the Auger coefficient (C_{Auger}) with narrowing bandgap.³⁰ Nonradiative Auger scattering scales as $C_{\text{Auger}}n^2$, where n is the carrier density. As shown in Fig. 12, SLDs operate at very high carrier densities, and combined with an increasing Auger coefficient with decreasing bandgap, longer wave SLDs

will operate with increased nonradiative carrier recombination, lower efficiency, and greater heating.

Comparing the results here to the mesa diodes in Ref [5,6], room-temperature, continuous-wave output powers in mesa diodes (surface emitters) are of the same order in absolute output power as the results demonstrated here for SLD waveguides (edge emitters). The mesa diodes have used bulk emission regions in contrast to the quantum wells here. The thicker emission regions allow mesa diodes to operate at lower current densities, reducing the impact of Auger scattering, while SLDs use quantum wells which operate at higher current densities, but are engineered to have lower Auger coefficients. On the other hand, if we compare maximum radiances (power/area/solid angle), mesa diodes do much worse: about 1 W/cm²/sr for mesa diodes in Refs [5,6] compared to 38 kW/cm²/sr for edge emitting SLDs, a five order of magnitude difference. The much higher radiance of SLDs is due to the very small surface area of an edge emitting SLD compared to the larger emission area of a surface emitting mesa diode, and may be of use for coupling the output power to small apertures of waveguides and fiber optics.

Simulations suggest significant improvements in SLD output could come from engineering of the photonic modes around the waveguide to suppress spontaneous emission out of the waveguide, and additional bandgap engineering to further suppress Auger scattering.

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GaSb Cap (50nm) p-doped 5×10^{18}
Graded Layer
Al(50%)GaAs(4.2%)Sb (2000nm) p-doped 5×10^{18}
Graded Layer
Al(25%)GaAs(2.1%)Sb (200nm) p-doped 1×10^{17}
QW x3 [In(42.2%)GaAs(14%)Sb (10nm)/ Al(25%)GaAs(2.1%)Sb (20nm)]
Al(25%)GaAs(4.2%)Sb (180nm) n-doped 1×10^{17}
Graded Layer
Al(50%)GaAs(4.2%)Sb (2000nm) n-doped 5×10^{18}
Graded Layer
GaSb Buffer (2000nm) n-doped 5×10^{18}
2" n++ doped GaSb Substrate

Fig. 1.
Stack diagram of the heterostructure grown for the superluminescent diode in this study.

Fig. 2.

(a) Optical interferometric image (2 nm vertical resolution) of a quantum well sample consisting of one 14 nm/ 20 nm $\text{Ga}_{0.58}\text{In}_{0.42}\text{As}_{0.14}\text{Sb}_{0.86}/\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}_{0.02}\text{Sb}_{0.98}$ quantum well with 100 nm $\text{Al}_{0.50}\text{Ga}_{0.50}\text{As}_{0.04}\text{Sb}_{0.96}$ clads plus a 5 nm GaSb cap grown at 450 C. (b) Measured high resolution xray diffraction rocking curve of the heterostructure in Fig. 1 (solid, black) compared to a simulation of the ideal structure with fully coherent layers (red, dashed).

Fig. 3.

Power out versus current in curve for a 2.4 μm laser diode fabricated from the structure shown in Fig. 1 as a 2 mm, straight waveguide with uncoated, normal facets.

Fig. 4.

Inverse (external) differential quantum efficiency versus waveguide length (triangular points) for straight waveguide laser diodes with structure as shown in Fig. 1. The solid lines are calculated using Eq. 11 for two different values of waveguide loss α_i

Fig. 5. Range of behaviors for light out versus current at 5% duty cycle in angled waveguide structures. Chip 1 shows superlinear growth characteristic of superluminescence. Chips 2 and 3 show low output superluminescence and lasing, respectively, likely due to facet imperfections.

Fig. 6. Spectrally resolved output of Chip 1. Spectral narrowing is evident with increasing current density, a characteristic of amplified spontaneous emission due to a nonuniform spectral gain profile.

Fig. 7.

Spectrally resolved output of Chip 2. Spectral narrowing is evident with increasing current density, indicative of amplification of spontaneous emission, but is accompanied by a blue shift, indicative of band filling.

Fig. 8.

Full width at half maximum of the waveguide output along the slow axis as a function of current density (points). The decreasing angular width of the output with increasing current density is an indication that amplification of spontaneous emission is growing.

Fig. 9. Spectral output of Chip 3. The several narrow output peaks, each less than 0.1 meV, are indicative of lasing on several cavity modes

Fig. 10.

Plot of wallplug, quantum, and differential efficiencies as a function of current density for Chip 1, the brighter superluminescent device at room temperature. All efficiencies are calculated using “useful” external emission, that is, emission out of one facet. Emission out of the opposite facet, and spontaneous emission out of the waveguide are not included.

Fig. 11.

Comparison between the measured superluminescent output of Chip 1 and the simulated output according to the theory of Sec. IID, showing good qualitative agreement. The simulation shows superlinear growth in output occurs after the active region becomes transparent (220 A/cm^2), then knees upward as gain increases and lasing threshold is approached.

Fig. 12.

Simulated carrier density in the superluminescent device, corresponding to output in Fig. 11. The redline shows the threshold carrier density of an equivalent straight waveguide laser diode, as in Fig. 3. The comparison emphasizes that carrier concentration does not clamp in a superluminescent diode, but continues to increase with current density.

Fig. 13. Simulations comparing improvements in output to base parameters for varying Auger coefficient (C), fraction of spontaneous emission into the waveguide mode (β_{sp}), and facet reflection (R).