Segmented 1.55um Laser with 400% Differential Quantum Efficiency

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Abstract:

By electrically segmenting, and series-connecting an InP ridge laser, we have demonstrated 12-stage lasers with 409% differential efficiency and 2.6mA threshold, as well as 3-stage lasers with 51ohm input impedance and 126% differential efficiency.

Introduction

Differential Quantum Efficiency (DQE), the ratio of photons emitted to electrons injected in a laser above threshold, can be of great importance in laser design. High DQE is critical in direct modulation schemes, and efficiencies beyond unity allow such applications as lossless taps (when modulated by a detector), efficient wavelength converters (if the laser is tunable), and the quantum-optic Photon Number Amplifier[1]. DQE is conventionally limited (if a good AR coating is used) by injection efficiency, the fraction of electrons which recombine in the active region and participate in stimulated emission. While this latter can be improved with novel structures, these rapidly approach the asymptotic limit of 100% injection. Further improvement in injection efficiency and DQE requires that the current pass through the device multiple times, or through multiple diodes sharing the same optical cavity. Past work[2-5] in this area has been of limited success, with 100% DQE barely exceeded only in vertical cavity lasers, either at short wavelengths[2] or under pulsed conditions[3].

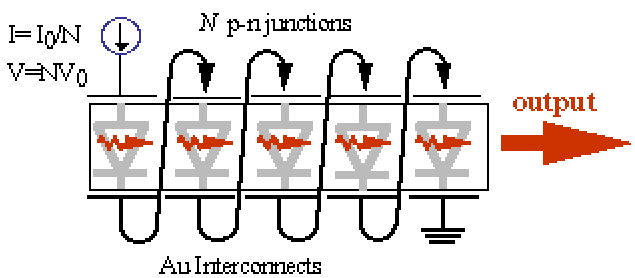

Figure 1a. Schematic of multistage laser. Ion implantation between stages forces current through the Au interconnects and through the diode chain.

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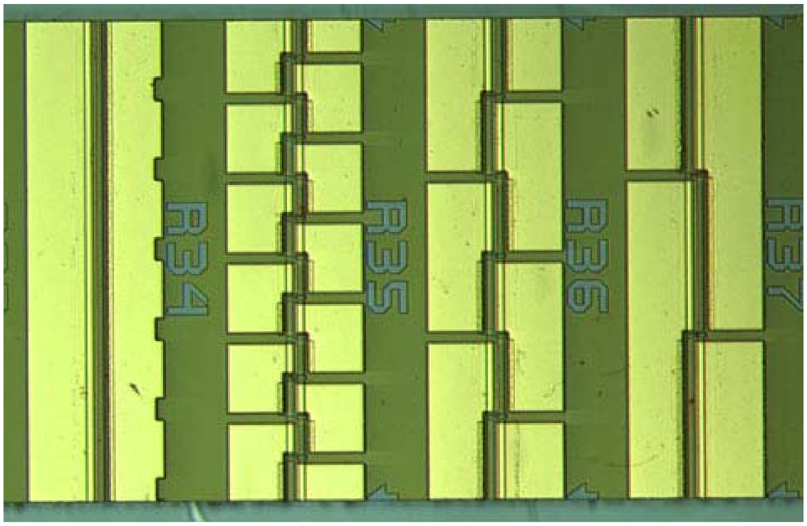

Figure 1b. Micrograph of 600um laser bar, showing (from left) 1, 12, 6, 3 stage lasers

We have pursued the technique, shown schematically in Figure 1a, of electrically segmenting a ridge laser along its length, and series-connecting these segments, directing the current through multiple diodes[4,5]. The same current density (and hence, optical operation), is achieved with N times less terminal current; this results in a differential efficiency N times higher, reflecting N passes through the diode chain. This idealized case requires optically transparent segmentation between stages, so we rely on ion implantation to eliminate leakage between stages, while minimizing the optical loss these implantations create.

Critical Technology

Ion implantation is commonly used in semiconductor devices to create insulating regions: the implant causes damage that reduces carrier lifetime and mobility to near-zero levels. Unfortunately, these conditions also make for an ideal photon sink, since when light is absorbed by implanted quantum wells (QW's), the electron-hole pair instantly recombines nonradiatively. If nothing is done to prevent this, a 3um-long implanted stripe, which electrically segments adjacent stages, will absorb 40% of the light passing through it.
To avoid this problem, we have used Implantation-Induced Quantum Well Intermixing (II-QWI) to blueshift the absorption edge in the implantation area to beyond the lasing wavelength. Modifying the technique pioneered by Charbonneau[6], we grow an undoped sacrificial layer above the waveguide, shallowly implant with P^+ to create defects near the surface, then anneal at 700°C to drive these defects downward, intermixing the QW's in the P^+-implanted regions. The sacrificial layer is etched down to an unblemished InP layer, a p-doped cap is regrown, and the sample is processed as described later.

Our intermixing method[7] eliminates the problem of Zn diffusion by conducting the blueshifting anneal before Zn is added to the structure, and stabilizes the intermixed material by immediately removing the source of the defects. It also allows us to separately optimize the intermixing conditions, rather than struggling to make them compatible with a pre-existing p-doped cap.

Process

The segmented laser uses a conventional ridge laser geometry and structure, as shown in Figure 2. The active region of 7 compressively strained InGaAsP 1.55um QW's is centered on a 4200Å waveguide of 1.3Q InGaAsP. This sits above an 10000Å n-InP layer, with a buried n+ 1.1Q InGaAsP layer serving as a n-contact layer, and a (100) InP substrate that is Fe-doped to prevent interstage leakage under the laser. As mentioned earlier, the first growth concludes with a 4500Å undoped, sacrificial InP layer for QWI, which is removed and replaced with a 20000Å p-InP/InGaAs cap during MOCVD regrowth.

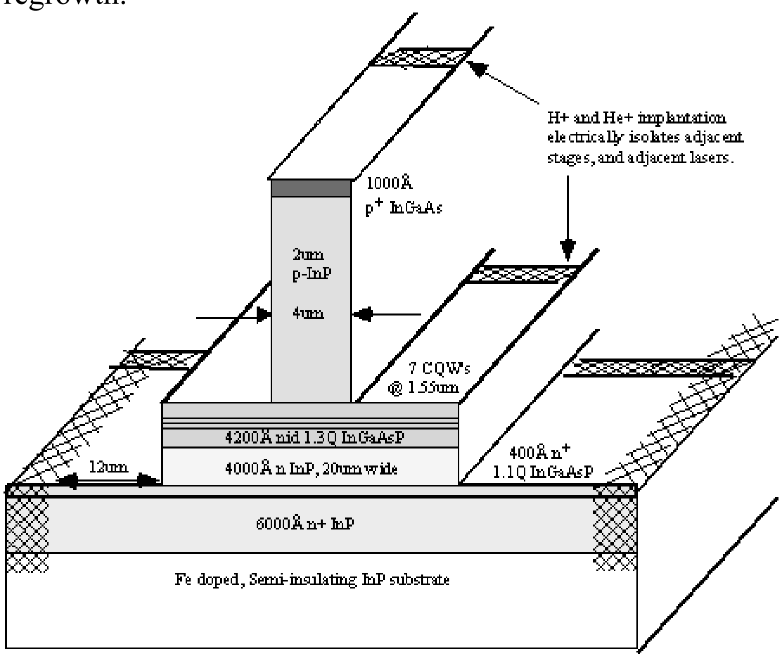

Figure 2. Cross-section of segmented laser, showing epitaxial structure, and device geometry

A 4um laser stripe is etched down to the waveguide, then a centered 20um stripe is etched down to expose the n-contact layer. After Ni/AuGe/Ni/Au n-contacts are deposited and annealed, the sample is coated in SiN_x, and a 3um Au mask defines 3um lateral stripes for interstage isolation. The sample is implanted with H^+ and He^+ to kill carrier lifetime in p- and n-doped regions, through to the semi-insulating substrate.

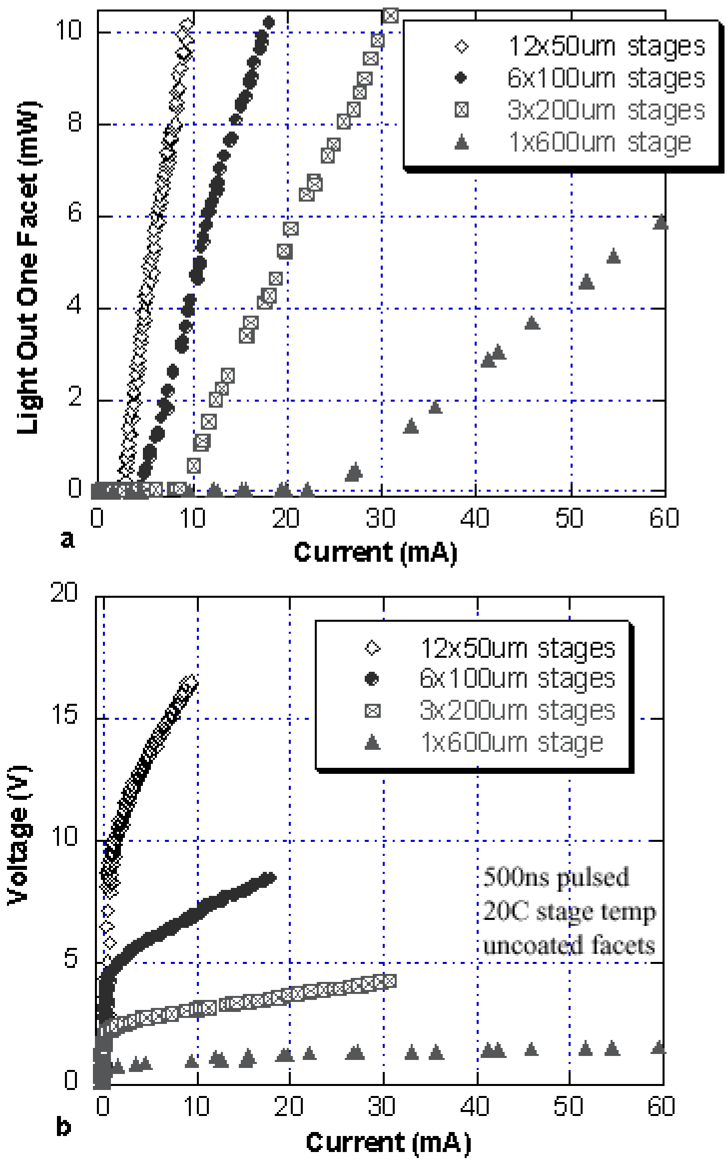

Figure 3. Pulsed L-I and V-I characteristics of three segmented one adjacent control laser.

Finally, the SiN is etched to open contact windows, and Ti/Pt/Au is evaporated and annealed to serve as a p-contact and interconnect layer. The samples were thinned, cleaved into 600um laser bars, and are not yet AR/HR coated. The finished device, shown in Figure 1b, illustrates lasers with 1, 3, 6, and 12 stages.

Results

The success of the above QWI and device processes is remarkably demonstrated by the laser curves in Figure 3. Each division into smaller stages multiplies the DQE and divides the threshold current by nearly the number of stages, culminating in a 12-stage x 50um laser with 409% pulsed DQE, and 2.6mA threshold current. Table 1 compares the characteristics of a bar with 3, 6, and 12-stage lasers to their adjacent control laser. These lasers are above average, but by no means exceptional: a 1000um, 19-stage laser clearly demonstrated 640% DQE up to 5mW per facet.

Table 1. Optical and electrical characteristics of the segmented lasers shown in Figure 3.

Laser Type	Differential Efficiency	Threshold Current	Threshold Voltage	Differential Resistance
600um control	42.4%	24.5 mA	1.25 V	7.6 ohms
3x200um stages	126%	8.7 mA	3.0 V	51.5 ohms
6x100um stages	222%	4.8 mA	5.9 V	217 ohms
12x50um stages	409%	2.6 mA	11.7 V	771 ohms

Time has not yet permitted proper mounting and heat-sinking for CW testing, but the lasers do operate up to 13mW CW when placed unmounted on a 20°C stage, as shown in Figure 4. Threshold current increases to 2.85mA, and DQE decreases to 342%, yet this is, to our knowledge, the first CW operation of any 1.55µm laser over 100% DQE, and certainly a world record. We look forward to reporting, at OFC, the CW performance of these lasers once they are properly heat-sunk.

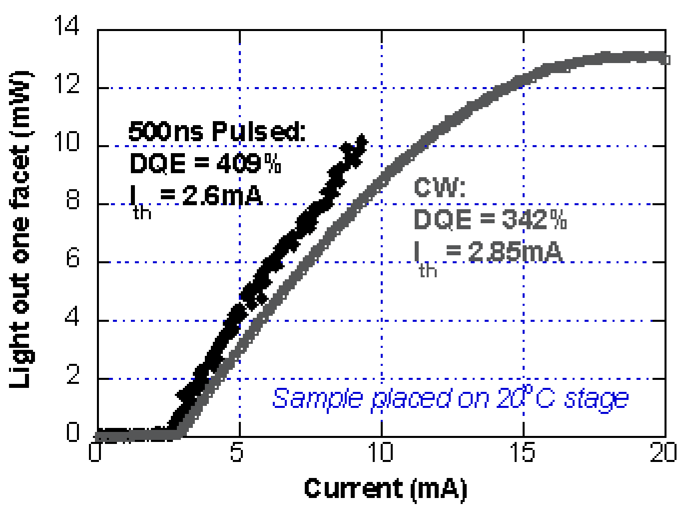

Figure 4. CW and pulsed operation of a 12-stage laser

The drawback of multistage lasers is that higher voltages are required to drive many highly resistive stages. In some cases, this is certainly problematic, and for a fixed laser length, differential resistance scales as the square as the number of stages (as demonstrated in Table 1). Fortunately, capacitance is reduced by the same amount, and the magnified resistance can be put to good use when impedance matching is important. The three-stage laser in Figure 3 has an input impedance of 51.5 ohms, and a modest threshold voltage of 3.0 V.

Analysis of control lasers has extracted several parameters of interest. Internal loss of $12.2cm^{-1}$ is excellent for a 7-QW active region, and indicates that the Zn-free II-QWI process has eliminated a large source of optical loss. The injection efficiency of 69.4% is respectable but also an area for improvement. Curve fits indicate that the optical loss due to segmentation implants is 0.1-0.15 dB/segmentation, and could be slightly reduced; however, this is already better than the minimum scattering loss caused by an attempt to remove the QW's rather than intermix them.

Conclusions

We have demonstrated a practical, robust, multistage laser, with DQE several times higher than unity. This efficiency is ultimately limited by impractically high voltages and resistances, as well as by the finite length of the optically dead, electrical segmentations. However, it is already high enough to drastically improve direct-modulation systems, offset fiber-coupling losses and make a lossless integrated wavelength converter without electrical amplification, or investigate noise properties of quantum optics.

References

1. H. Yuen, "Amplification of quantum states and noiseless photon amplifiers," *Physics Lett.* vol. 113A, pp. 405-7, January, 1986.
2. W. Schmid, et al, "CW operation of a diode cascade InGaAs quantum well VCSEL," *Electronics Letters*, vol. 34, pp. 553-5, March 1998.
3. J. Kim, et al, "Epitaxially stacked, multiple active region 1.55um lasers for increased differential efficiency," *Applied Phys. Lett.* vol. 74, pp. 3251-3, March 1999.
4. S.G. Ayling, et al, "Intrinsically matched 50 ohm laser arrays with greater than 100% quantum efficiencies for optically coupled transistors and low-loss fibre optic links,' SPIE Photonics West, Optoelectronics '98: Laser Diode Applications IV, paper 36, January, 1998.
5. J. Getty, et al, "Monolithic, series-connected segmented-ridge lasers," *Electron. Lett.* vol 35, pp.1257-8, July, 1999.
6. S. Charbonneau, et al, "Quantum well intermixing for optoelectronic integration using high energy ion implantation," *J. Appl. Phys.*, vol. 78, pp. 3697-3705, September, 1995.
7. E. Skogen, et al, "Tunable sampled-grating DBR lasers using quantum-well intermixing." *Photonics Technology Letters*, vol.14, pp. 1243-5, September, 2002.