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PHOTONICS SPECTRA

Addressing Inefficiency in Diode Lasers

by Jason Farmer, nLight

At the time the Super High Efficiency Diode Sources (SHEDS) program started in September 2003, nLight's highest-performing 940-nm semiconductor lasers operated near 50 percent overall efficiency. In little more than a year, the improvements described here and others have enabled the company to demonstrate high-power semiconductor lasers with efficiencies of more than 70 percent.

With the focus on efficiency provided by SHEDS, a clear experimental path that will enable 75 percent efficiency in the near future has been identified. The goal is 80 percent by September 2006. This is clearly achievable, and it will set the path for a revolutionary class of high-power semiconductor lasers.

nLight is taking a direct approach to the design and fabrication of diode lasers that can meet the goals of the SHEDS program. It is targeting three key sources that limit the overall efficiency of today's commercially available diode lasers to 50 percent: voltage drop, the energy expended in getting charge carriers (holes and electrons) from the electrodes across the semiconductor and into the quantum well; lost electron-hole pairs, the energy lost when holes and electrons recombine without producing a laser photon; and lost laser photons, the energy lost when photons are absorbed or scattered before leaving the resonator.

Voltage drop

Each photon generated in a semiconductor laser has a certain amount of energy. In an ideal device, each injected electron-hole pair would have exactly this energy. However, in a real semiconductor laser, each pair must have additional energy that is expended in moving it from the metal leads into the semiconductor (contact resistance), through each layer of semiconductor material (bulk resistance) and, finally, across each junction between the dissimilar semiconductor materials that together constitute the laser structure (heterobarrier voltage drop). This additional energy in each electron-hole pair is deposited as heat in the laser and can be measured as an "excess voltage."

The company, in collaboration with P. Daniel Dapkus of the University of Southern California in Los Angeles, is working on a laser design that eliminates the heterobarrier voltage drop. In standard semiconductor laser designs, the carriers are injected from the top and bottom of the laser structure and therefore traverse all the heterobarriers (junctions between the various semiconductor layers). However, by etching deep grooves through the structure, carriers can be injected directly into the active region (Figure 1).

In this way, all of the heterobarriers are avoided. As a result, the extra amount of energy typically required to traverse them and the intervening material is unnecessary. This

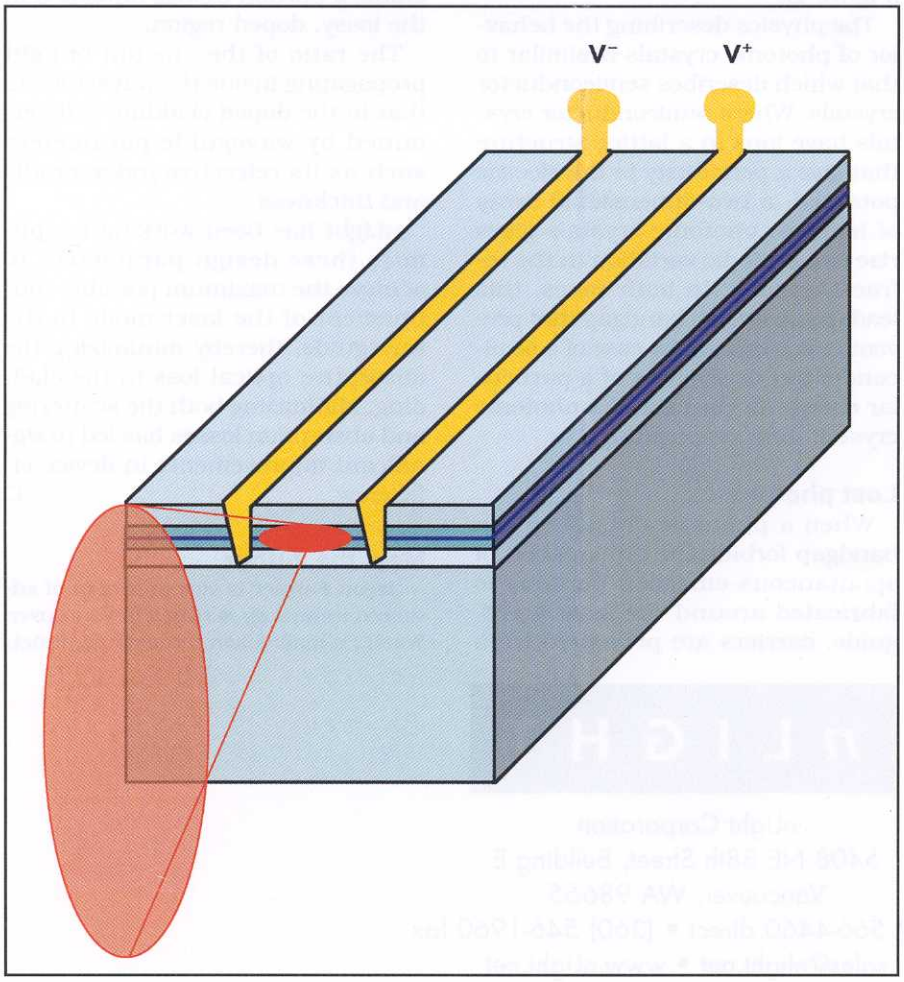

Figure 1. By etching gold-filled grooves in the semiconductor diode, carriers are laterally injected directly into the quantum well. This eliminates the energy-consuming voltage drops across the heterostructures.

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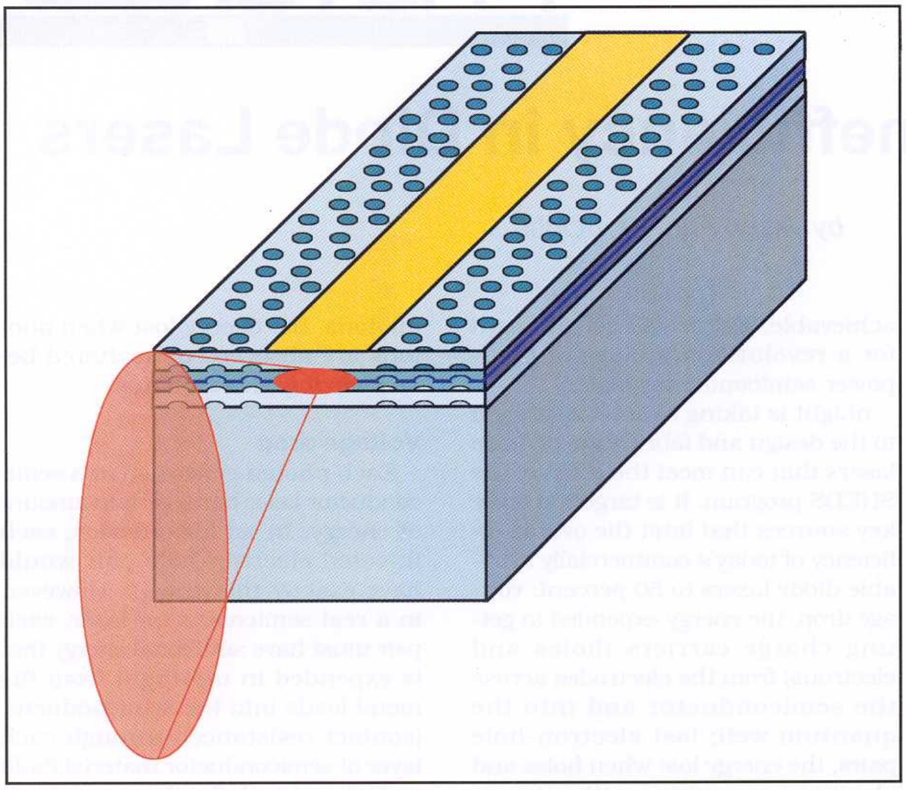

Figure 2. Photonic crystals work to reduce spontaneous emission by preventing carriers from emitting photons in an undesired direction.

leads to a dramatic reduction in voltage drop that significantly improves the efficiency of the device.

Lost electron-hole pairs

The carriers injected into the active region of a semiconductor laser combine to create photons. This combination can happen either when stimulated by another photon (stimulated emission) or spontaneously (spontaneous emission). Stimulated emission results in optical gain that amplifies light. Spontaneous emission occurs in random directions and random phases and does not contribute to gain.

Together with John D. O'Brien at the University of Southern California, nLight is working on laser designs that make use of photonic crystals to reduce spontaneous emission. Photonic crystals create an optical bandgap that prevents light from propagating in undesired directions (Figure 2).

The physics describing the behavior of photonic crystals is similar to that which describes semiconductor crystals. Where semiconductor crystals have ions in a lattice structure that give a periodicity to the electric potential, a two-dimensional array of holes in photonic crystals gives rise to a periodic variation in the refractive index. In both cases, this leads to an energy bandgap that prevents electrons (in the case of a semiconductor) or photons of a particular energy (in the case of a photonic crystal) from propagating.

Lost photons

When a photonic crystal whose bandgap forbids the propagation of spontaneous-emission photons is fabricated around the laser waveguide, carriers are prevented from emitting photons in this direction. This leaves more carriers available to create optical gain, which reduces the threshold current and improves the efficiency of the device.

Once an electron-hole pair recombines via stimulated emission, the laser photon that it generates must exit the front facet before it emerges as useful output. While they are still in the laser, photons can be lost through either absorption or scattering within the device structure.

The company is decreasing scattering losses through materials growth studies that offer means to reduce the density of crystal defects and the roughness of interfaces that scatter light. The primary source of absorption is in the doped region of the laser structure outside the waveguide. Although the majority of the laser light is confined to the waveguide, a portion travels outside it in the lossy, doped region.

The ratio of the amount of light propagating inside the waveguide to that in the doped cladding is determined by waveguide parameters such as its refractive index profile and thickness.

nLight has been working to optimize these design parameters to achieve the maximum possible confinement of the laser mode to the waveguide, thereby minimizing the absorptive optical loss in the cladding. Minimizing both the scattering and absorption losses has led to significant improvements in device efficiency. ☐

Meet the author

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