Invited Paper

High-power broadened-waveguide InGaAsSb/AlGaAsSb quantum-well diode lasers emitting at 2 μm

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ABSTRACT

We review our recent progress in the design and operation of 2-μm InGaAsSb/AlGaAsSb quantum-well diode lasers. The devices have InGaAsSb quantum-well active regions and AlGaAsSb cladding layers, and all were grown lattice-matched to GaSb substrates using molecular-beam epitaxy. The broadened-waveguide (BW) design produces internal losses as low as 2 cm^{-1}, which leads to external quantum efficiencies as high as 53%. Single-quantum-well lasers with 200-μm apertures and 2-mm-long cavities exhibit output powers of 1.9 W CW and 4 W quasi-CW. The lowest threshold current densities are 115 A/cm^2. Small arrays of similar multi-quantum-well diodes emit 10.6 W CW. The broadened-waveguide design should improve the performance of all mid-infrared diode lasers.

Keywords: semiconductor diode lasers, 2 μm wavelength, broadened-waveguide lasers, high-power, InGaAsSb, AlGaAsSb

1. INTRODUCTION

There are many applications for mid-infrared lasers emitting at wavelengths ≥ 2 μm. These include trace-gas sensing[1]; pumping Ho-YAG solid-state lasers[2] or mid-infrared semiconductor lasers[3]; and infrared countermeasures. The key to the applicability of these devices is room-temperature, efficient operation. This is especially true in cases demanding high output power. To improve the efficiency of diode lasers, we have altered the design of conventional, quantum-well (QW), separate-confinement-heterostructure (SCH), diode lasers[4]. The SCH layers have been broadened, resulting in devices exhibiting higher power and higher efficiency than conventional SCH diode lasers. The improvement stems from a dramatic reduction of internal optical losses effected by the BW design. In this paper we summarize our results using the BW design for 2-μm antimonide lasers[1,4-8]. Reference 9 discusses the details of the BW design concept. The BW concept has also been successfully applied to 1.5-μm InGaAsP/InP lasers[10], to 0.81-μm AlGaAs/GaAs diode lasers[9], and to 0.97- and 0.99-μm Al-free lasers[11,12].

First, we briefly describe the BW concept in Section 2. The performance of BW lasers is presented in Section 3 and compared with that of conventionally designed lasers. Conventional lasers have internal losses of tens of cm^{-1}, while the BW laser has a loss of 2 cm^{-1}. In Section 4 we discuss the characteristics of high-power BW-laser arrays outputting 10 W[7]. The performance of single-QW BW lasers is described in Section 5; these lasers output 1.9 W CW and 4 W quasi-CW with an external efficiency near threshold of 53%. Section 6 contains a summary of our results and our conclusions.

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2. THE BROADENED-WAVEGUIDE CONCEPT

The BW concept is illustrated schematically in Fig. 1.

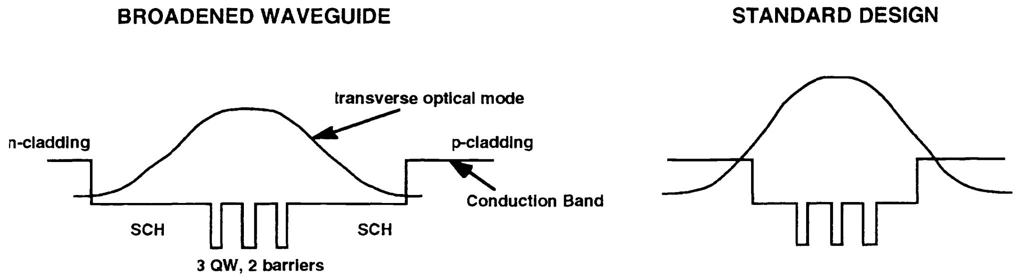

Figure 1. The schematic conduction-band profile of a broadened-waveguide 3-quantum-well laser compared with that of a standard design. The transverse optical modes are shown as well.

The conduction-band profiles for a BW and a standard design are shown schematically, along with the transverse optical modes. Each design incorporates three QWs surrounded by separate-confinement heterostructure (SCH) layers and cladding layers. Maximal overlap of the mode with the QWs, Γ_{QW}, determines the SCH width in the standard design. The distinguishing feature of the BW structure is its wider SCH layers, thus leading to a wider, or broadened, optical waveguide. The broadened waveguide, unlike the standard design, has a smaller percentage of the optical mode in the doped cladding layers, in which optical losses from free-carrier absorption can be large, especially in the p-cladding layer. Cladding layers are usually doped as heavily as possible to minimize Ohmic losses. BW lasers should, therefore, exhibit lower internal losses. Since free-carrier absorption increases as a power of the wavelength, such optical losses are greater for longer-wavelength semiconductor lasers.

A consequence of the BW design is that Γ_{QW} is lower, and hence the threshold currents, I_{th}, in BW lasers may be higher. It will be seen below that I_{th} is virtually unaffected in BW lasers. Moreover, high-power lasers are driven at currents many times I_{th}, so the important laser parameter is the external efficiency, $\eta_d = \eta_i \alpha_{out}/(\alpha_{out} + \alpha_i)$ [photons/electron]. η_i is the internal quantum efficiency. α_{out} combines the output-facet losses: $\alpha_{out} = -\ln(R_1R_2)/2L$ [cm^{-1}], where R_1 and R_2 are the facet reflectivities, and L is the laser cavity length. α_i [cm^{-1}] is the internal optical loss.

3. THE PERFORMANCE OF 5-QW BROADENED-WAVEGUIDE LASERS

We characterized 2-μm antimonide-based diode lasers with varying degrees of waveguide broadening[5]. Figure 2 shows schematically the general energy-band diagram of the lasers. The band-offset data of Tsou[13] were used to construct the diagram. The structures were grown by molecular-beam epitaxy on GaSb substrates[6].

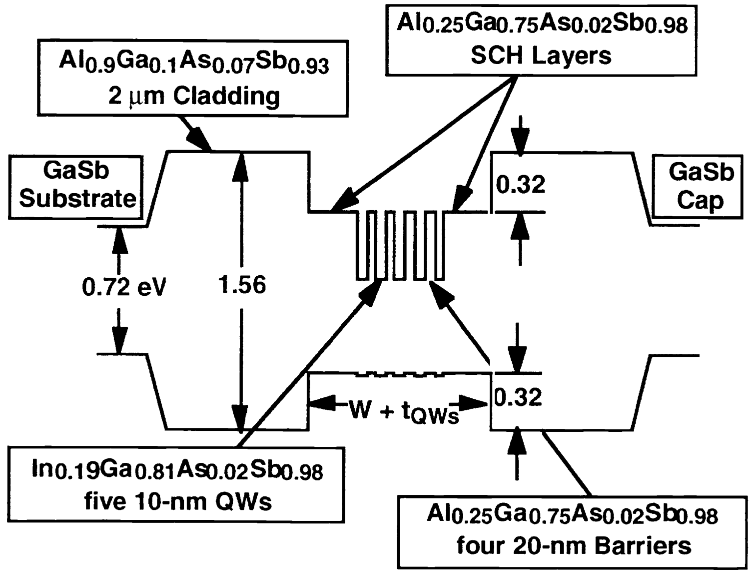

Figure 2. The energy-band diagram of InGaAsSb/AlGaAsSb/GaSb lasers used to study the effects of waveguide broadening.

There are compositionally graded regions between the n-substrate/n-cladding-layer and the p-cladding-layer/p^{++}-GaSb-cap to facilitate majority carrier flow from the low- into the high-bandgap compounds. The devices all contained five 10-nm-wide $In_{0.19}Ga_{0.81}As_{0.02}Sb_{0.98}$ QWs. The SCH layers and the 20-nm-wide barriers were $Al_{0.25}Ga_{0.75}As_{0.02}Sb_{0.98}$, and the 2-μm-thick cladding layers were $Al_{0.90}Ga_{0.10}As_{0.07}Sb_{0.93}$. Broadening the waveguide was accomplished by symmetrically widening the SCH layers to give a width W for the total thickness of the SCH and barrier layers.

Fabry-Perot lasers with 100- or 200-μm-wide apertures, S, were made with three waveguide thicknesses: W = 0.12, 0.32, and 0.88 μm. The cavity lengths, L, varied from 0.5 to 2 mm, and in some cases low-reflect, LR (3%), and high-reflect, HR (95%), coatings were applied to the laser facets.

Figure 3 shows the CW output-power characteristics for three 2-mm-long lasers, each with a different waveguide thickness. For optimal cooling the lasers were indium-soldered junction-side, or epi-side, down to a copper heatsink. The heatsink temperature increased from 10 °C at threshold to 15 °C at the maximum output power level. All three lasers had 100-μm apertures and 2-mm cavities.

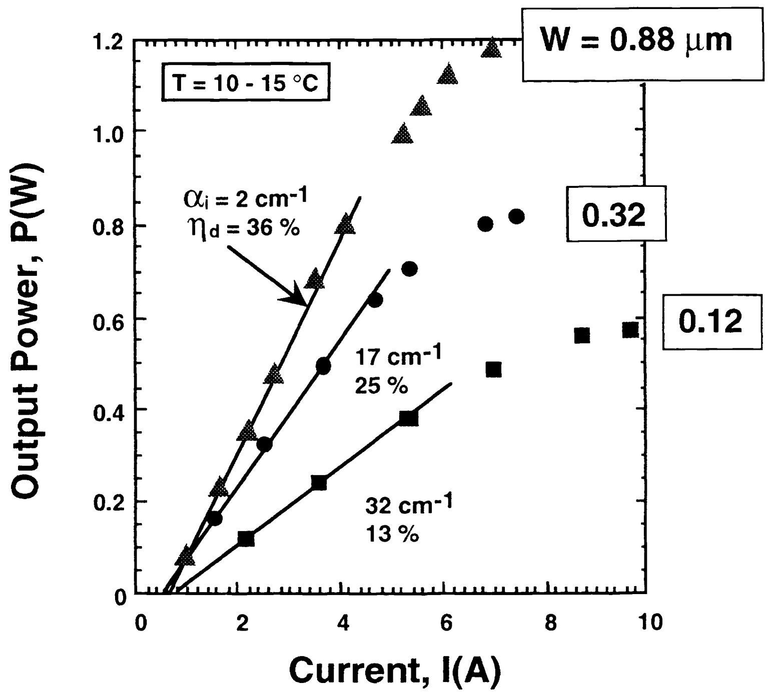

Figure 3. CW Output-power characteristics for lasers with waveguide thicknesses of 0.12, 0.32, and 0.88 μm.

The devices' facets were HR-LR coated. Also indicated in Fig. 3 are the external differential efficiencies, η_d, and the internal losses, α_i. For each laser, α_i was inferred from the standard analysis of $(1/\eta_d)$-vs-L, using diodes of various cavity lengths[9].

Broadening the waveguide from 0.12 to 0.88 μm decreases α_i from 32 to 2 cm^{-1}. Likewise, η_d increases from 13 to 36%. The threshold currents for all three lasers are about 0.7 A (350 A/cm^2), which suggests that the decrease in Γ_{QW} for a BW laser is compensated by the decrease in α_i. As a consequence of the reduction in the internal losses as W increases, the maximum output power increases from 0.6 to 1.2 W. These results show that the BW design affords increased power from a given QW device.

Figure 4 shows the spectra from a 2-μm BW laser (W = 0.88 μm) taken at 15 °C for output powers of 10 and 100 mW.

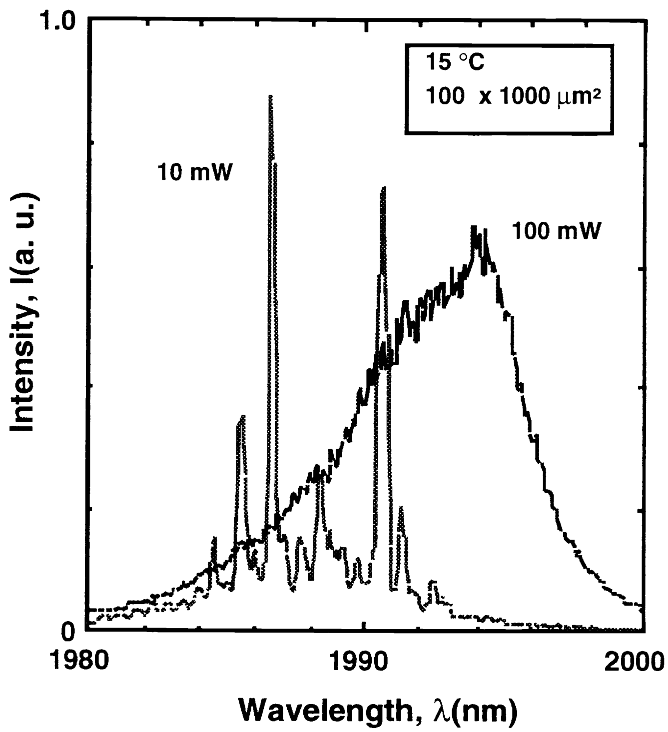

Figure 4. The spectra of a broadened-waveguide laser for CW output powers of 10 and 100 mW.

The laser is 1-mm and has a 100-µm aperture. At 10 mW, the spectrum is centered at about 1987 nm, and its mode structure is evident. The spectrum shifts to longer wavelength at 100 mW owing to heating, and it becomes dense with modes. The width of the spectrum at half power is about 10 nm. This is typical behavior for a Fabry-Perot laser, since no mode-selection mechanism is built into the device.

4. HIGH-POWER 2-µm LASER ARRAYS

The low internal loss of BW lasers means that the Fabry-Perot cavity can be made relatively long. This reduces output losses. The thermal and electrical resistances of the laser die are each proportional to L^{-1}, so that at diode currents, I, where $I \geq I_{th}$, the BW laser temperature is lowered, and the output power increases.

We fabricated arrays of 2-µm BW lasers[7]. Figure 5 shows a schematic diagram of a mounted 20-element array.

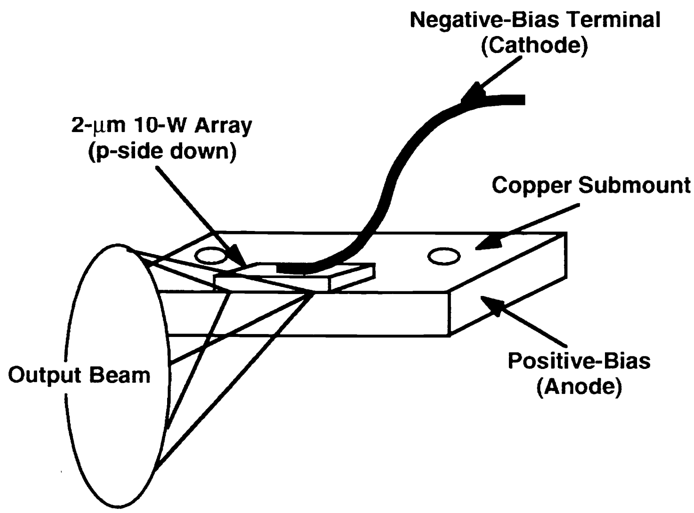

Figure 5. Schematic diagram of a mounted 20-element array of 2-µm BW lasers.

The array comprises two 10-element bars mounted p-side, or epi-side, down. The center-to-center aperture spacing is 500 µm. During characterization, the copper submount is bolted to a liquid-cooled heatsink.

Figure 6 shows the output-power characteristic of the array. The threshold current is 12.5 A, or 0.625 A per device in the array.

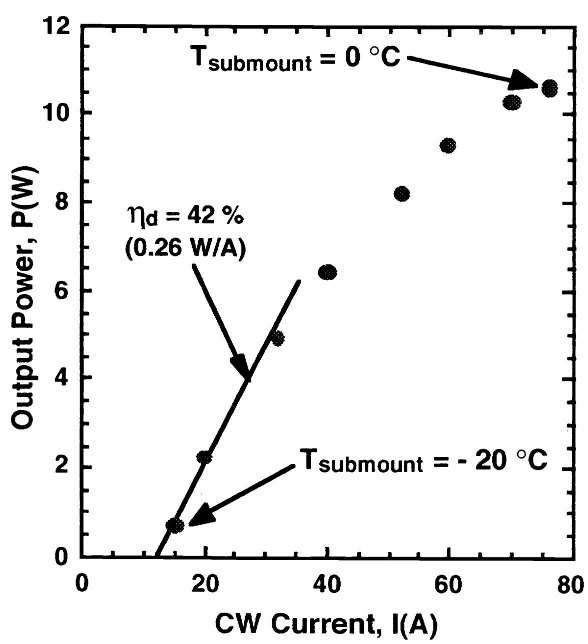

Figure 6. The CW output-power characteristic of a 20-element array of 5-QW, 2-µm BW lasers (W = 0.88 µm). The cavity lengths are 2 mm, and the apertures are 200 µm.

This is slightly lower than I_{th} = 0.7 A for the devices in Fig. 3, which had 100-μm apertures, but the submount temperature is -20 °C in the present case. Near threshold η_d is 42%. The maximum power is 10.6 W at 76 A drive current, at which power the submount temperature has risen to 0 °C. This power is higher than the previous record at 2-μm[14]. Arrays such as these are ideal as pumps for Ho-YAG solid-state lasers, since the quantum defect is small.

5. SINGLE-QUANTUM-WELL BROADENED-WAVEGUIDE LASERS

The low internal loss of BW lasers allows the number of QWs to be reduced, since as mentioned above, cavity lengths can be increased, thereby decreasing output losses. High power can, therefore, be achieved with fewer QWs. In addition, fewer QWs should result in less interfacial optical scattering, thus further lowering α_i.

Figure 7 shows the output-power characteristics taken at 10 °C for a single-QW BW laser operating in the CW and quasi-CW (qCW) modes[14].

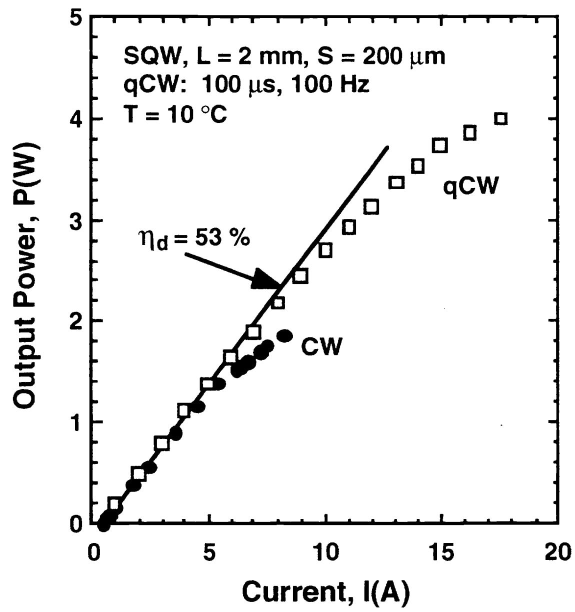

Figure 7. CW and quasi-CW (qCW) output power characteristics for a single-QW broadened-waveguide laser.

During qCW operation, the laser was driven with 100-μs current pulses at a 100-Hz rate. The device had a 2-mm cavity and a 200-μm aperture. The threshold current is 460 mA (115 A/cm^2). This is among the lowest threshold current densities measured for 2-μm antimonide lasers[15, 16]. Near threshold for both CW and qCW operation, η_d is 53%, again one of the highest values reported for this type of device. The maximum CW power is 1.9 W, which is higher than the previous record[12]. In the qCW mode the output power reaches 4 W at a drive current of 17.6 A. The qCW power is higher than the CW power because the heat dissipation is less.

These results clearly demonstrate the benefits of the BW design: lower internal optical losses with no penalizing increase in threshold current. This enhancement leads to efficient, high-power devices.

6. SUMMARY AND CONCLUSIONS

This work has shown that 2-μm InGaAsSb/AlGaAsSb/GaSb broadened-waveguide diode lasers exhibit internal optical losses as low as 2 cm^{-1}. These low losses are the result of minimizing free-carrier absorption in the cladding layers by using a waveguide that is about 7 times wider than the typical standard design. With internal losses reduced to a few cm^{-1}, long-cavity, high-power lasers are possible. Single-quantum-well, broadened-waveguide devices with 200-μm apertures and 2-mm cavities output 1.9 W CW and 4 W quasi-CW. The external efficiency is 53%, and the threshold current density is 115 A/cm^2. A 20-element array of BW lasers output 10.6 W CW. All of these are record output powers. While the broadened-waveguide design has effected dramatic improvements in 2-μm lasers, shorter-wavelength lasers have also shown improved performance using the broadened-waveguide design. For wavelengths greater than 2-μm, where free-carrier absorption is greater, the broadened-waveguide approach should be very beneficial.

7. ACKNOWLEDGMENTS

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