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ABSTRACT

High-power laser-diode arrays have been demonstrated to be viable pump sources for solid-state lasers. The diode bars (fill factor of 0.7) were bonded to silicon microchannel heatsinks for high-average-power operation. Over 12 W of CW output power was achieved from a one cm AlGaInP tensile-strained single-quantum-well laser diode bar. At 690 nm, a compressively-strained single-quantum-well laser-diode array produced 360 W/cm² per emitting aperture under CW operation, and 2.85 kW of pulsed power from a 3.8 cm² emitting-aperture array. InGaAs strained single-quantum-well laser diodes emitting at 900 nm produced 2.8 kW pulsed power from a 4.4 cm² emitting-aperture array.

1. INTRODUCTION

High-average-power laser diodes are becoming the preferred method of optical pumping solid-state lasers. Compared to flash-lamp pumps, diode-laser arrays offer the advantages of compact size, narrow band of emission, high optical fluence, and higher reliability. With the continued development of new material systems, laser diodes operating over a wide spectral range are allowing the realization of laser/ion host combinations that were not previously possible using flash-lamp pumps. In many cases, the absorption bands of various rare-earth and transition-metal laser ions are commensurate with the light emission from III-V laser diodes. As shown in Fig. 1, combining the column III elements (Al/Ga/In) with the column V elements (As/P) allows the lasing emission to span the ~ 0.62 μ m to 2.0 μ m wavelength range.^{1,2}

The most widely used solid-state laser is the Nd³⁺:Yttrium Aluminum Garnet (YAG) system emitting at 1.06 μ m (shown by the central lasing transition in the figure). An important feature of Nd³⁺ is that it forms a four-level-laser system, so it can be conveniently pumped by flash lamps (or by laser diodes emitting at 808 nm). Although Yb³⁺ is superior to Nd³⁺ in terms of energy storage, (the emission lifetime, typically > 1 ms, is roughly four times greater than Nd³⁺ for the same host medium), Yb³⁺ cannot be pumped effectively by flash lamps because of its quasi-three-level-laser electronic structure.³ Only with the development of high-power InGaAs diodes (emitting at $\geq$ 900 nm) has Yb been considered a viable dopant; laser diodes are now capable of generating sufficient intensity to create inversion and achieve lasing action in various Yb-doped crystals. Since the emission wavelength of Yb³⁺ (~ 1 μ m) is similar to Nd³⁺ in the same host, but is pumped at a longer wavelength, three to four times less thermal energy is deposited into the Yb-doped crystal. This can enhance the overall average-power performance of the laser since less thermal distortion is introduced for a given pump power. In addition, pumping at longer wavelength allows the incorporation of In into the active layer of AlGaAs-based laser diodes for increased reliability.⁴

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Fig. 1. Schematic diagram showing the absorption overlap of common rare-earth and transition-metal ions with the emission from III-V laser diodes.

Visible-emitting AlInGaP laser diodes are finding use in many commercial applications, including pump sources for diode-pumped solid-state lasers (DPSSLs). For solid-state laser applications requiring tunability, $\text{Cr}^{3+}:\text{LiSrAlF}_6$ (Cr:LiSAF) operating over the 0.77-1.0 μm wavelength range,⁵ and alexandrite operating over the 0.7-0.8 μm wavelength range,⁶ may be pumped by AlGaInP laser diodes operating between 620 nm and 690 nm. Alexandrite, in particular, could benefit from the high-average power densities afforded by laser-diode arrays; the thermal fracture limit and thermal conductivity are five and two times greater than YAG, respectively.⁷ Although, alexandrite may be pumped by a narrow absorption line (R1) at 680.4 nm,⁵ shorter wavelengths (i.e., ≤ 640 nm) would allow more efficient pumping of compact radially-pumped rod geometries, depending on the Cr^{3+} concentration. Moreover, precise wavelength control is not an issue because of the broad absorption band (centered near 600 nm), making a ~ 640 nm DPSSL easier to implement.

Although reliable visible diodes emitting low power levels do exist, it has been considerably more difficult to produce high-average-power laser diodes and arrays. Shifting the lasing emission to shorter wavelength reduces the conduction and valence band offsets, thereby increasing carrier leakage which translates into a lower differential quantum efficiency.⁸ The electrical resistance is two to three times that of comparable AlGaAs lasers, and the p -cladding layer of the AlGaInP-laser structure is at least twice as thermally resistive as AlGaAs-based structures. This relatively low conversion efficiency, exacerbated by higher thermal impedance, results in continuous wave (CW) performance that is poorer than pulsed operation for visible-emitting diodes. Similarly, due to the problem of heat dissipation the normalized CW output power of an array of emitters from a laser bar will be lower than that obtained from a corresponding single emitter. Operating visible lasers efficiently under high-average power, therefore, necessitates the use of an extremely aggressive heatsink.

2. HEATSINKING

To increase the emission intensity that is required for various end-pumped and side-pumped geometries, diode bars are stacked into linear arrays. The stacking pitch can be increased (as much as 25/linear cm) to attain high peak power (low duty factor) operation, but for high-average power and CW operation, the pitch density must be reduced (≤ 10 /linear cm) to ensure adequate cooling.⁹ In such cases, the silicon microchannel cooler offers superior performance (normalized thermal impedance < 0.015 $^{\circ}\text{C}\cdot\text{cm}^2/\text{W}$) in a practical architecture.¹⁰ A schematic diagram of a silicon microchannel heatsink array is shown in Fig. 2.

Fig. 2. Schematic diagram of a silicon microchannel heatsink array composed of five packages with 18 mm of linear bar per package.

As shown in the magnified view, water flows from the inlet holes into the etched-silicon manifold, across a borosilicate glass insert, to the silicon microchannel layer, and then exits through the outlet holes. The glass insert seals off the etched grooves (of both silicon layers) and guides the coolant directly towards the microchannels (not shown), which lie just beneath the diode. The noteworthy performance advantage of this heatsink comes from the incorporation of microchannels which lie just beneath the diode; their narrow width (20 μm) minimizes the stagnant boundary layer of water which contributes most to the thermal impedance of the package (the thermal conductivity of water at room temperature is ~ 250 times less than that of silicon). The microchannels also rely on laminar flow which consumes less hydraulic power than the turbulent flow found in the compact high intensity cooler (CHIC).⁹ Unlike diamond or copper heatsink materials, the silicon microchannels can be wet-etched using conventional means for ease of fabrication at reduced costs. Finally, arbitrarily large two dimensional arrays can be formed by stacking the individual packages between conductive elastomer gaskets. This modular design allows for ease of maintenance and introduces only two electrical and two water connections. A more detailed discussion of the design and characterization of the silicon microchannel heatsink can be found elsewhere.¹⁰

3. 640 nm LASER DIODES

The separate confinement heterostructure (SCH) laser diode used in this work is shown in Fig. 3; the design is similar to those reported previously.^{8,11} The material was grown by metal organic chemical vapor deposition (MOCVD) on a misorientated [(100) 10° off toward (111)] n^+ GaAs substrate. A single tensile-strained $\text{Ga}_{0.6}\text{In}_{0.4}\text{P}$ quantum well (120 Å) was confined by a pair of 1200 Å thick $(\text{Al}_{0.6}\text{Ga}_{0.4})_{0.5}\text{In}_{0.5}\text{P}$ layers, and the $\text{Al}_{0.5}\text{In}_{0.5}\text{P}$ cladding layers were 0.8 μm thick. To reduce the series resistance, a $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$ barrier-reduction layer (750 Å) was grown between the p -cladding layer and the 500 Å p^+ GaAs cap layer.

Fig. 3. Schematic diagram of the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}/\text{Ga}_{0.6}\text{In}_{0.4}\text{P}$ tensile-strained quantum well, separate confinement heterostructure.

The laser bars consist of $100\ \mu\text{m}$ wide emitters spaced on $140\ \mu\text{m}$ wide centers, giving a fill factor of 0.7. Each emitter was optically isolated from its neighbors by etching trenches down to the lower n-cladding layer. For v-groove fabrication, the GaAs cap was removed using a mixture of $\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ (5:1:1) at room temperature, and the remaining epitaxial layers were etched in sulfuric acid ($100\ ^\circ\text{C}$), which stops when the GaAs substrate is reached. Elevating the temperature of the sulfuric acid reduces the etch rate selectivity between the AlInP and GaInP layers.¹² SiO_2 (grown by chemical vapor deposition) produces a durable wet-etch mask, and is also used for the electrical isolation. The *p*-side was metallized with Ti/Pt/Au, and afterwards the wafer was thinned to a thickness of $\sim 100\ \mu\text{m}$. Ge/Au/Ni/Au was deposited onto the *n*-side and the wafer was then alloyed. After cleaving, the laser bar facets were coated using electron-beam evaporation. At an emission of $640\ \text{nm}$, the low reflector (LR) had a reflectivity of $\sim 10\%$ using a single layer of Al_2O_3 , and the high reflector (HR) had a reflectivity of $\sim 85\%$ using an alternating quarter wavelength stack of $\text{SiO}_2/\text{TiO}_2$ layers (optimized for $690\ \text{nm}$ emission). Once the laser bars were coated, they were indium-soldered, *p*-side down, to silicon microchannel heatsinks. Au wire bonds connected the *n*-side of the bar to the *n*-side contact of the package. In this work, all of the laser bars characterized in the laser arrays were unscreened.

The light-output (L-I) characteristics for a one cm long laser bar is shown in Fig. 4, using a $750\ \mu\text{m}$ cavity length. Under pulsed operation ($100\ \mu\text{s}$ at $10\ \text{Hz}$), the threshold current density (J_{th}) is roughly $525\ \text{A}/\text{cm}^2$ and the slope efficiency is $0.68\ \text{W}/\text{A}$; note that individual broad area lasers (uncoated) had a J_{th} as low as $455\ \text{A}/\text{cm}^2$ and a slope efficiency as high as $1.1\ \text{W}/\text{A}$ (sum of both facets) which illustrates the high quality of this material. As shown in the figure, $45\ \text{W}$ was obtained under pulsed conditions at $\sim 100\ \text{A}$, which was power supply limited. When the laser bar was operated CW, a maximum output power of $12.2\ \text{W}$ was attained, which represents a factor of two higher power level than previous reports.¹³ It has been shown, that a fill factor as high as 0.65 does not limit the CW performance of $690\ \text{nm}$ diodes.¹⁴ However, this may not be the case for $\lambda \leq 640\ \text{nm}$, in which the conversion efficiency has dropped considerably. Optimizing the fill factor for the given emission wavelength should increase the maximum possible output power.

Fig. 4. Light-output characteristics for a one cm long AlGaInP SCH laser bar with a 0.7 fill factor and a 750 μm cavity length. The device was pulsed at room temperature (23 $^{\circ}\text{C}$) and run CW at 11 $^{\circ}\text{C}$ at a ramp rate of 4 A/s. The microchannel heatsink was operated with 50 psi pressure at 150 cm^3/min flow rate.

At a drive current of 40 A (power level ~ 3 W), the peak emission intensity is centered at 640 nm, and the full width at half maximum (FWHM) is 4.9 nm. A wavelength shift equal to 0.16 nm/ $^{\circ}\text{C}$ was measured using low duty cycle pulses while varying the heatsink temperature ($\lambda = 636$ nm at room temperature). Based on the measured shift of wavelength versus temperature, the thermal impedance of the package is only 0.020 $^{\circ}\text{C}\text{-cm}^2/\text{W}$ for this cavity length.¹⁵

4. 690 nm LASER DIODES

Separate confinement heterostructure (SCH) and graded index separate confinement heterostructure (GRINSCH) lasers are similar to those used previously at 640 nm, except that a thin compressively-strained quantum well is used for the longer visible emission (e.g., 690 nm). The SCH structure incorporated 0.9 μm $\text{Al}_{0.5}\text{In}_{0.5}\text{P}$ cladding layers. The p -cladding layer was Si-doped at $2 \times 10^{18} \text{ cm}^{-3}$, and the n -cladding layer was Zn-doped at $6 \times 10^{17} \text{ cm}^{-3}$. A single compressively-strained 80 $\text{\AA}$ $\text{Ga}_{0.43}\text{In}_{0.57}\text{P}$ quantum well was confined by $(\text{Al}_{0.6}\text{Ga}_{0.4})_{0.5}\text{In}_{0.5}\text{P}$ barrier layers, 0.14 μm in thickness. A 0.1 μm $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$ hetero-barrier reduction layer was introduced between the p -cladding and a 0.1 μm GaAs cap layer. The GRINSCH structure comprised 0.12 μm barrier layers graded from $\text{Al}_{0.3}\text{GaIn}_y\text{P} < \text{Al}_x\text{GaIn}_y\text{P} < \text{Al}_{0.7}\text{GaIn}_y\text{P}$, where y was varied to maintain lattice matching to the GaAs substrate. Also, the hetero-barrier reduction layer was reduced to 0.05 μm , the cladding layers were 1.0 μm thick, the quantum well was 70 $\text{\AA}$ thick, and the material was doped similarly to the SCH structure. In the following study, the SCH and GRINSCH structures behaved similarly; any slight light-output performance differences were attributed to nonuniform material quality. The diode bars were fabricated and coated in parallel with the 640 nm diode bars. The output coatings had $\sim 10\%$ and $> 95\%$ output reflectivities for the LR and HR side, respectively.

The light-output (L - I) characteristic for a one cm long, 800 μm cavity length, AlGaInP laser bar is shown in Fig. 5 under pulsed conditions (100 μs pulse with a 1 kHz repetition rate) with the coolant held at 23 $^{\circ}\text{C}$. The threshold current density (J_{th}) is roughly 310 A/ cm^2 ; the soft-turn on behavior is attributed to nonuniformity in the individual emitters across the length of the bar. A slope efficiency of 1.2 W/A (DQE = 65%) and a peak conversion efficiency (η_c) of $\sim 35\%$ was obtained at 73 W, at the onset of thermal rollover. Note that this conversion efficiency accounts for power dissipated

in the package, as well as in the diode. The same laser bar was operated under CW conditions at 40 W with no visible change in threshold current or slope efficiency.¹⁶

Fig. 5. Light-output characteristics for a one cm long AlGaInP SCH laser bar with a 800 μm cavity length. The device was pulsed at room temperature (23 °C) at a ramp rate of 4 A/s. The microchannel heatsink was operated with 50 psi pressure at 150 cm³/min flow rate.

Fig. 6. Emission spectrum from an AlGaInP GRINSCH laser bar with a bar length of 1.8 cm. The spectrum was taken CW at 100 A, and the heatsink was operated at 12 °C with 50 psi pressure and 150 cm³/min flow rate.

The output spectrum of a single package (composed of two 9 mm bars adjoined together) is shown in Fig. 6 under CW operation. At a drive current of 100 A, the peak emission intensity is centered near 690 nm, and the full width at half maximum (FWHM) is 2.5 nm. A wavelength shift equal to 0.16 nm/°C was measured, consistent with the data taken for the 640 nm diodes.

To evaluate the performance of the AlGaInP laser bars in a realistic pumping architecture, a linear array was formed by stacking together five laser bar packages; each package contained 1.8 cm of lasing material, and the total assembly occupied a one square cm of emitting aperture.¹⁷ The L-I curve for this array is shown in Fig. 7 under CW operation, using a ramp rate of 4 A/s. At 50 psi pressure and 750 cm³/min flow rate, the array only consumes 4.3 W of hydraulic power. As shown, an output power level of 360 W was obtained, which was power supply limited. The slope efficiency (1.0 W/A) and peak conversion efficiency (33%) of the array are the same values found for the individual packages, since there is no thermal penalty from stacking bars together.

Fig. 7. Light-output characteristics for the AlGaInP GRINSCH laser bar array comprising five packages. The footprint of this assembly consumes one square cm of emitting aperture (at the outside dimension of the silicon packages).¹⁷ The heatsink assembly was operated at 12 °C with 50 psi pressure and 750 cm³/min flow rate, consuming 4.3 W of hydraulic power.

As described previously, arbitrarily large arrays can be easily constructed using silicon microchannel heatsinks. In the following example (Fig. 8), an array was fabricated from 19 packages, consuming 3.8 square cm of emitting aperture. The array was tested with 100 μs long pulses. At low duty cycle (0.1%), 2.85 kW of power was attained before reaching the power supply limit. There is only a slight degradation in slope efficiency when the duty cycle is increased to 20%; again, the output power is supply limited.

Fig. 8. Light-output characteristics for AlGaInP GRINSCH laser array composed of 19 packages. The heatsink was operated at 16 °C with 50 psi pressure.

5. 900 nm LASER DIODES

The laser diode structure was grown by metal organic chemical vapor deposition (MOCVD) on a misorientated [(100) 2° off toward (110)] n^+ GaAs substrate. The device structure comprised 1.5 μm $\text{Al}_{0.6}\text{Ga}_{0.4}\text{As}$ cladding layers and 0.2 μm compositionally graded transitions ($x = 0.6$ to 0.3) to a 100 Å $\text{In}_{0.03}\text{Ga}_{0.97}\text{As}$ strained quantum well. Absent from this structure are GaAs layers typically found on either side of the quantum well;¹⁸ such layers are not appropriate here owing to the resulting poor carrier confinement and to the high absorption coefficient ($\sim 40 \text{ cm}^{-1}$) of GaAs at 900 nm.¹⁹ The processing details are the same as those prescribed for the visible material except for the v-groove fabrication, which uses a conventional etch of $\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ (1:8:1). At an emission wavelength of 900 nm, the output coatings had $\sim 10\%$ and $> 95\%$ output reflectivities for the LR and HR side, respectively.

In many applications, including the optical pumping of $\text{Yb}^{3+}:\text{Sr}_5(\text{PO}_4)_3\text{F}$ (Yb:S-FAP) by 900 nm diodes,²⁰ the laser-diode-emission must be radiance-conditioned by collimating the fast axis (perpendicular to the junction plane) through the use of a cylindrical microlens which rests on the front of the package. The lens collects the emitted light up to 60° (1 Rad) divergence and collimates it to approximately 0.6° (10 mRad). With a microlens attached to the package, the diode bar must be reduced to 15 mm in length. A detailed discussion of the microlens technology is given elsewhere.²¹ An array comprising 22 microlens-conditioned packages was built to pump a diode-pumped Yb:S-FAP laser. The L-I characteristics for the InGaAs laser bar array are shown in Fig. 9. The relatively long 1000 μm cavity length was chosen to minimize chirp during the 1 ms pulse duration. The slope efficiency was $= 1.0 \text{ W/A}$ (per bar), with a J_{th} of 150 A/cm^2 . The total array generated up to 2.8 kW of pulsed power (10 Hz at 1 ms long pulses, commensurate with the Yb^{3+} lifetime). By microlens-conditioning the diode emission, up to 23 kW/cm^2 was extracted from a light pipe used to irradiate the rod.

Fig. 9. Light-output characteristics for InGaAs laser array composed of 22 packages. The diode bars were 1.5 cm in length to accommodate microlens conditioning at the output facet. The heatsink was operated at 15 °C with 50 psi pressure.

For efficient operation of a DPSSL, the emission wavelength of the diode array must closely overlap the absorption band of the crystal host. As an example, Fig. 10 shows the measured double-pass transmission (i.e., absorption inverted) compared to the emission spectrum of the InGaAs array. Due to the excellent uniformity of the epitaxial growth, the FWHM linewidth of the array is 6.5 nm at 10 °C with 140 A drive current, and the emission lies at the Yb^{3+} :S-FAP absorption center.

Fig. 10. Transmission spectrum of the Yb^{3+} :S-FAP rod overlaps the laser emission from the InGaAs laser bar array.

6. CONCLUSION

Progress in the AlGaInP material system has produced visible-emitting laser diodes with greater reliability, higher output performance, and shorter wavelengths than previously anticipated. However, heat dissipation of AlGaInP diode bars under high-average-power operation still remains a vexing problem. Through the use of silicon microchannel heatsinks, high-power CW laser bars are capable of emission between 640 nm and 690 nm, which can be used to pump several tunable laser-host media, such as alexandrite and Cr:LiSAF. Collimating the laser-diode emission allows still higher output intensities, enabling quasi-three-level solid-state lasers (e.g., Yb) to be realized via diode pumping. In this work, an InGaAs array was used to demonstrate a diode-pumped Yb³⁺:S-FAP laser. Similarly designed Yb-doped DPSSLs could be used to augment or replace flash-lamp and diode-pumped Nd³⁺:YAG lasers in future commercial applications.

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