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ULTRALOW BEAM DIVERGENCE AND INCREASED LATERAL BRIGHTNESS IN OPTICALLY PUMPED MIDINFRARED LASER (POSTPRINT)

Ron Kaspi, et al.

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AIR FORCE RESEARCH LABORATORY
Directed Energy Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

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14. ABSTRACT
An optically pumped edge-emitting semiconductor laser emitting near 4.1 μm was designed with weak transverse mode confinement resulting in an exceptionally large transverse optical mode size. Consequently, a laser device is reported that exhibits a fast-axis divergence angle of $\sim$4.2° full-width at half-maximum (FWHM). More notably, a large reduction of the lateral axis divergence is also observed as a result of the increased lateral coherency. The reduced confinement factor and differential gain serves to suppress lateral filamentation. Despite the higher threshold and lower power, a lateral divergence angle of $\sim$3.2° FWHM and increased lateral brightness is achieved.

15. SUBJECT TERMS
Antimonide laser, low beam divergence, midinfrared laser, optically pumped laser, type-II quantum wells

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Ultralow Beam Divergence and Increased Lateral Brightness in Optically Pumped Midinfrared Laser

Ron Kaspi, Michael L. Tilton, Gregory C. Dente, Joseph R. Chavez, and Andrew P. Ongstad

***Abstract*— An optically pumped edge-emitting semiconductor laser emitting near 4.1 μm was designed with weak transverse mode confinement resulting in an exceptionally large transverse optical mode size. Consequently, a laser device is reported that exhibits a fast-axis divergence angle of ~4.2° full-width at half-maximum (FWHM). More notably, a large reduction of the lateral axis divergence is also observed as a result of the increased lateral coherency. The reduced confinement factor and differential gain serves to suppress lateral filamentation. Despite the higher threshold and lower power, a lateral divergence angle of ~3.2° FWHM and increased lateral brightness is achieved.**

***Index Terms*— Antimonide laser, low beam divergence, midinfrared laser, optically pumped laser, type-II quantum wells.**

I. Introduction

In epitaxially grown edge-emitting semiconductor lasers, the waveguide is typically engineered to provide a large modal overlap with the gain region so that low threshold and high slope efficiencies can be achieved. As the gain region is contained within the epitaxial growth, the transverse mode of the device is correspondingly thin, typically only a few micrometers. In a p-i-n junction diode laser, the transverse mode size is further restricted by the necessity to flow current across this junction while minimizing resistive heating. Diode laser designs must often mitigate between minimizing the thickness of the undoped gain region to reduce the operating voltage, and maximizing the undoped gain region to reduce waveguide losses arising from the penetration of the mode into doped clad regions. These considerations result in semiconductor edge-emitting lasers that exhibit a relatively large transverse axis divergence angle when compared to other large mode-size devices such as solid-state disk or fiber lasers. The fast-axis beam divergence, whether from a 980nm semiconductor laser diode, or a midinfrared quantum cascade laser, typically ranges between 20 to 40 degrees as measured at the full-width at half-maximum (FWHM) point, [1] unless additional beam shaping features such as plasmonic collimation gratings are added [2]. Such a large divergence makes it difficult to capture and manipulate the output beam, and is a distinct disadvantage of semiconductor lasers.

In optically pumped semiconductor laser designs, waveguide clad layers do not need to be intentionally doped. As a result, there is additional flexibility in the design of the waveguide without fear of extensive waveguide loss in the clad regions. In this letter, we demonstrate that an optically pumped device can be engineered to deliberately extend the transverse mode a very large distance into the substrate. As a result, devices with ultralow fast-axis divergence angles can be produced. As an important added benefit of the reduced overlap with the gain region, we also find that the lateral spatial coherence of the device is also greatly improved, resulting in ultralow lateral divergence from a broad area optically pumped laser.

II. Experiment

The semiconductor heterostructure design used in this experiment is similar to previously reported edge-emitting optically pumped semiconductor lasers (OPSL) grown on GaSb:Te (001) substrates. [3] The heterostructure consists of a 0.2-μm-thick GaSb buffer layer, followed by a ~2-μm-thick lattice-matched $In_{0.16}Ga_{0.84}As_ySb_{1-y}$ waveguide core region containing fourteen $InAs/In_{0.4}Ga_{0.6}Sb/InAs$ type-II quantum wells to provide gain. This is followed by a ~4-μm-thick GaSb undoped top clad layer. Finally, a 0.5-μm-thick nearly-lattice-matched low-index $AlAs_{1-y}Sb_y$ cap layer is grown to prohibit the transverse mode from extending beyond the device when it is in the epi-down configuration. The quaternary alloy of the waveguide is designed to absorb the 1.9-μm pump radiation to create electron-hole pairs. These carriers recombine in the quantum wells to produce emission near 4.1 μm. The transverse mode is only weakly confined by the GaSb substrate at the bottom and the GaSb top clad, with refractive indexes only slightly lower than that of the waveguide core.

The experiment was designed to manipulate the extension of the transverse mode into the GaSb substrate by using three different GaSb:Te substrates, each with a different nominal doping concentration. The refractive index of the GaSb substrate is expected to decrease as the tellurium dopant concentration is increased [4]. Laser-A was grown on a substrate with a nominal carrier concentration of $1.4-1.6\times10^{18}/cm^3$ measured at room temperature. For Laser-B, the carrier concentration was estimated to be $2.6-2.8\times10^{17}/cm^3$. Finally for Laser-C, the nominal carrier concentration was $1-2\times10^{16}/cm^3$.

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The authors are with the Air Force Research Laboratory, Albuquerque, NM 87117 USA (e-mail: Ron.Kaspi@kirtland.af.mil; michael.tilton@kirtland.af.mil; gcdente@gmail.com; joseph.chavez2@kirtland.af.mil; andrew.ongstad@kirtland.af.mil).

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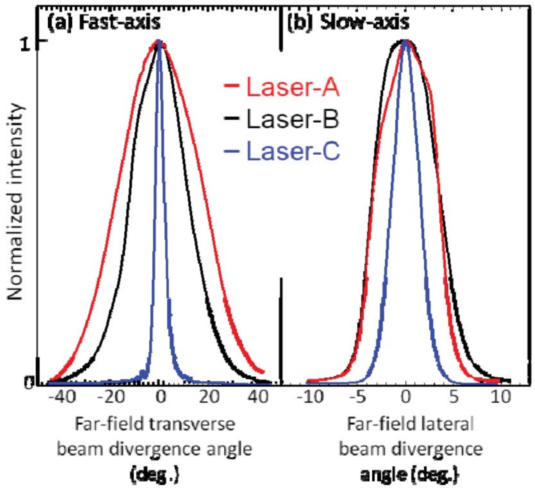

Fig. 1. (a) Far-field transverse beam profile comparison between Laser-A, -B, and -C. (b) Far-field lateral-beam profile comparison between Laser-A, -B, and -C.

The laser structure was grown simultaneously on all three wafers, and thus identical. It is expected that the transverse mode will be most confined and least extended in Laser-A, and the least confined and most extended in Laser-C.

Devices were lapped and polished to a nominal thickness of 120-microns, cleaved to a 4mm cavity-length, and mounted epi-down for characterization at 80K. The width of the gain-guided device was ∼250-microns, defined by the width of the pump stripe. The 1.9-μm pump radiation is not absorbed by the GaSb substrate, thus making epi-down mounting possible. The output power, spectra, and far-field characteristics were measured using 32-μsec pulses at 1% duty-cycle.

III. Results

Fast axis beam profile measurements from all three devices collected at the highest pump power available are presented in Figure 1(a). Laser-A exhibits a divergence angle of ∼39 degrees as measured at the FWHM. Laser-B exhibits a reduced fast-axis divergence of ∼26 degrees, consistent with a larger transverse mode. In Laser-C, we observe a divergence angle of only ∼4.2 degrees FWHM, confirming a very large transverse mode size.

Slow-axis beam profile measurements are presented in Figure 1(b). Given that these are broad-area devices, this divergence angle is primarily determined by the dimension of the lateral filaments that are formed. Laser-A and Laser-B exhibit a similar lateral beam divergence of ∼7.5 degrees at FWHM, considerably smaller than what is typically observed in broad-area semiconductor diode lasers [1]. Such optically pumped devices were previously shown to provide some protection against filament formation due to a very small line-width enhancement factor α, typically ∼1 [5]. In contrast, Laser-C exhibits a lateral beam divergence of only ∼3.2 degrees at FWHM, indicating a further increase in filament size and improved lateral coherency. Evidently, the much larger transverse mode size, along with the corresponding reduction of the confinement factor, Γ, resulted in a substantial increase of the coherency of the lateral beam in these broad area devices.

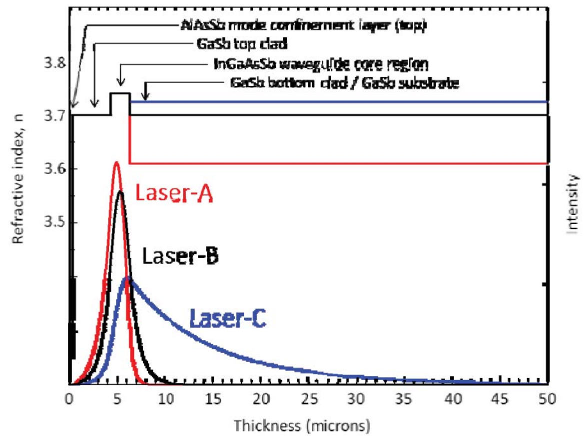

Fig. 2. Calculated transverse modes generated using the substrate refractive index as a fitting parameter to the observed far-field profile. Also shown is the refractive index variation with thickness for Laser-A, -B, and -C.

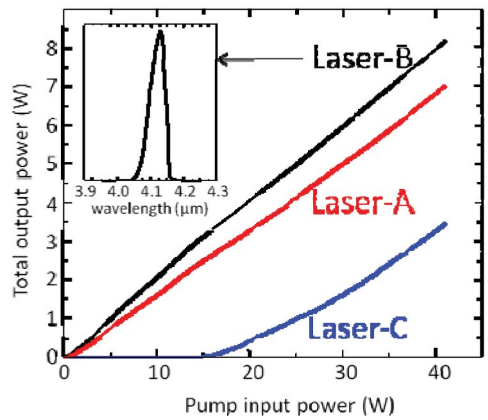

Fig. 3. Input power versus total output power measured at 80 K from Laser-A, -B, and -C. Emission spectrum from Laser-B is shown in the inset.

Using a complex waveguide model, the refractive index of the different substrates was used as the fitting parameter to match the far-field profiles and estimate the extent of the transverse mode. A refractive index value of n∼3.74 at 80K was assumed for the waveguide core region. For the substrates of Lasers-A, -B and -C, a refractive index of n∼3.61, n∼3.70, and n∼3.725, produced good fits, respectively. The calculated transverse modes are shown in Figure 2. The transverse mode in Laser-C likely reaches approximately 50 micrometers into the substrate due to the extremely low index confinement provided by the waveguide region. We also calculated a reduced core region confinement factor, Γ, in Laser-C, that is approximately four times smaller than that in Laser-B.

With a large reduction in Γ, we can expect Laser-C to exhibit increased threshold power relative to Laser-A and Laser-B. The power-power curves for all three devices are shown in Figure 3, and this is indeed the case. The threshold power in both Laser-A and Laser-B is approximately ∼150W/cm^2, whereas the threshold power in Laser-C is

TABLE I
LASER CHARACTERISTICS

	$\theta_{\perp}$	$\theta_{=}$	$d_{\perp}$	$d_{=}$	Output Power	Brightness (MW/ cm^2-sr)
Laser-A	39°	7.5°	7.5-μm	250-μm	7.0 W	1.0
Laser-B	26°	7.5°	8.0-μm	250-μm	8.2 W	1.2
Laser-C	4.2°	3.2°	50-μm	250-μm	3.5 W	2.5

~1.6 kW/cm^2. Laser-B exhibits the highest total output power, ~8.2 Watts from two facets at ~42W of input power, the maximum available. Laser-A produced ~7 Watts of output power due to the slightly lower slope efficiency, presumably as a result of the increased free-carrier losses in the higher doped substrate. Due to the much larger threshold power and slightly lower slope efficiency, laser-C was only able to produce ~3.5W at the maximum pump power, albeit with increased lateral coherency. The brightness for a diode laser can be defined as:

$$B = \frac{Output\ Power}{\pi^2 \cdot \left(BPP_{\perp}^2 + BPP_{=}^2\right)}, \quad (1)$$

where the Beam Parameter Products (BPP's) in the two orthogonal directions (fast and slow axis) are defined as:

$$BPP_{\perp} = \left(\frac{\theta_{\perp}}{2}\right) \cdot \left(\frac{d_{\perp}}{2}\right)$$
$$BPP_{=} = \left(\frac{\theta_{=}}{2}\right) \cdot \left(\frac{d_{=}}{2}\right) \quad (2)$$

θ and d are the full angular divergences and beam diameters in the respective perpendicular and parallel directions. We can calculate the relative brightness of Laser-B and Laser-C, operating under identical conditions, at the maximum input pump power of ~42W. Table I lists the measured and calculated characteristics for each of the lasers.

Laser-B's brightness is estimated to be ~1.2 MW/cm^2-sr. In contrast, Laser-C's brightness is estimated to be ~2.5 MW/cm^2-sr. Laser-C is capable of producing more than twice the brightness of Laser-B despite its lower output power. This is a direct result of the increased lateral coherence. The fast-axis emission remains near-diffraction limited despite the difference in divergence angle.

The improved lateral coherency and suppressed filament formation in broad-area lasers with extended transverse modes and reduced modal gain overlap can be understood by analyzing the carrier-induced filament formation process near steady-state [6]. The analysis shows that filament gain can be reduced when the line-width enhancement factor, (α), is minimized, when the internal losses, (a), are reduced, or alternatively when the saturation intensity, (I_s), is increased. Because the epitaxial structures were equivalent in this letter, we can expect that α and a are similar.

With the carriers clamped at threshold, the expression for I_s is given by:

$$I_s = \frac{\eta_i \ V_{gap}}{\Gamma \ \frac{\partial G}{\partial J}} \quad (3)$$

where η_i is the injection efficiency, G is the gain, J is the current density, and V_{gap} is the gap voltage. When the confinement factor Γ in Laser-C is reduced, the threshold gain is increased, resulting also in a reduction in the differential gain. Through the inverse dependence of I_s on both Γ and ∂G/∂J, the extended transverse mode will have the effect of increasing the saturation intensity, thus reducing the filament gain. Laser-C is therefore an embodiment of one of the design principles needed to reduce the tendency for lateral filamentation in a broad area laser. [6]

In addition to the nearly cylindrical output beam with very low divergence that is easier to capture and manipulate, and the improved lateral coherency which leads to increased brightness, there are two other good reasons to use a laser designed to support an extended transverse mode. One of these is the reduced photon flux at the facet which will protect against possible heating and facet damage. The other is the fact that external coupling to the laser mode is made easier as a result of the large mode size.

IV. CONCLUSION

We demonstrate that the transverse mode size can be deliberately extended in an optically pumped design to produce semiconductor edge-emitting lasers with ultralow fast-axis divergence. The resulting increase in threshold density and lower output power does not necessarily result in reduced brightness. This is because an additional benefit of the reduced confinement factor is the suppression of lateral filaments due to the increased saturation intensity. These design principles, put forward in reference 6, are used here to produce midinfrared lasers with increased brightness.

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