Ultra-low beam divergence and increased lateral brightness in optically pumped mid-infrared laser

Ron Kaspi*, Michael L. Tilton, Gregory C. Dente, Andrew P. Ongstad, Chi Yang
Air Force Research Laboratory, Directed Energy Directorate AFRL/RDLAS,
3550 Aberdeen Ave., Albuquerque, New Mexico USA 87117

BIOGRAPHY

Ron Kaspi: Born in Istanbul, Turkey in 1962, Dr. Kaspi received his bachelor's degree in Mechanical Engineering from Duke University, his master's degree in Materials Engineering from Rutgers University in 1986, and his Ph.D. in Materials Science and Engineering from Northwestern University in 1991. With expertise in the area of molecular beam epitaxy (MBE) of semiconductor heterostructures, Dr. Kaspi's early research focused on surface segregation of alloys, interfacial mixing, and in-situ sensing during MBE. More recently, Dr. Kaspi has concentrated his efforts in the area of semiconductor mid-infrared lasers. He has developed and advanced the optically pumped semiconductor laser (OPSL), designed to emit in the mid-IR wavelengths using the antimonide family of semiconductors. Dr. Kaspi is currently a senior research scientist at the Air Force Research Laboratory in Albuquerque, NM, where he leads a group of scientists in developing semiconductor mid-infrared lasers that provide high brightness for a variety of applications. Dr. Kaspi is a fellow of the OSA.

TECHNICAL ABSTRACT

We have conducted a study in which we demonstrate that an optically pumped device can be engineered to extend the transverse mode a very large distance into the substrate. As a result, devices with ultra-low 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 ultra-low lateral divergence from a broad area optically pumped laser.[1] Due to the latter, the brightness of the device is substantially increased.

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. The laser heterostructure consisted of a GaSb buffer layer, followed by a 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 was followed by a thick GaSb undoped top clad layer.

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 [2]. Laser-A was grown on a substrate with a nominal carrier concentration of $1.4\text{-}1.6\text{x}10^{18}/\text{cm}^3$ measured at room temperature. For Laser-B, the carrier concentration was estimated to be $2.6\text{-}2.8\text{x}10^{17}/\text{cm}^3$. Finally for Laser-C, the nominal carrier concentration was $1\text{-}2\text{x}10^{16}/\text{cm}^3$. The laser structure was grown simultaneously on all three wafers, and thus identical. The transverse mode was most confined and least extended in Laser-A, and the least confined and most extended in Laser-C. Calculated transverse modes generated using the substrate refractive index as a fitting parameter to the observed far-field profile for Laser-A, Laser-B, and Laser-C are shown in Figure 1.

Fast axis beam profile measurements from all three devices collected at the highest pump power available are presented in Figure 2(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, demonstrating that the transverse mode size can be deliberately extended in an optically pumped design to produce semiconductor edge-emitting lasers with ultra-low fast-axis diver-

*ron.kaspi@kirtland.af.mil; phone (505)846-5879

gence. This is the smallest fast-axis divergence angle exhibited by an edge-emitting laser that does not contain additional beam shaping features such as plasmonic collimation gratings. [3]

Slow-axis beam profile measurements are presented in Figure 2(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, already considerably smaller than what is typically observed in broad-area semiconductor diode lasers. 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.

When the confinement factor Γ in Laser-C is reduced, the threshold gain is increased, resulting in an increase in threshold pump density and lower output power. Despite this, a ~2x increase in brightness is measured.[1] This is because an additional benefit of the reduced confinement factor is the suppression of lateral filaments due to the increased saturation intensity. An analysis of carrier-induced filament formation near steady-state shows that the extended transverse mode will have the effect of increasing the saturation intensity, reducing the filament gain.[4] This design principle, is used here to produce mid-infrared lasers with increased brightness.

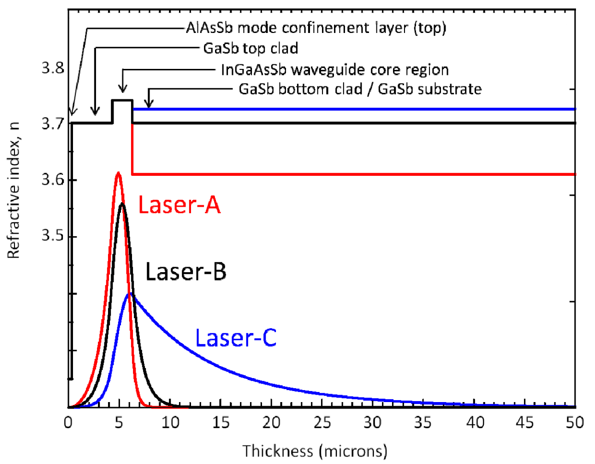

Figure 1.

Calculated transverse modes generated using the substrate refractive index as a fitting parameter to the observed far-field profile.

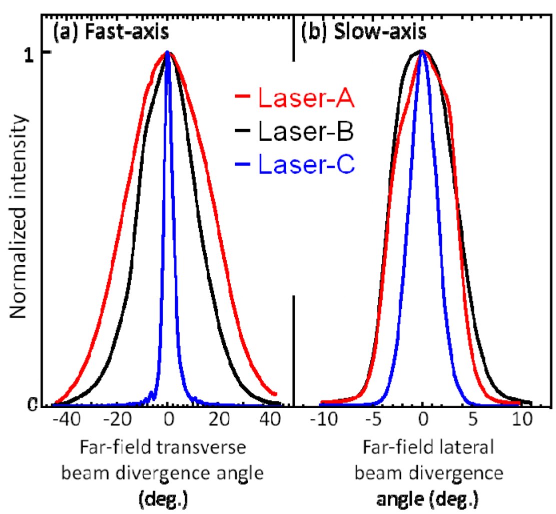

Figure 2.

(a) Far-field transverse beam profiles for Laser-A, Laser-B, and Laser-C; (b) far-field lateral-beam profiles for Laser-A, Laser-B, and Laser-C.

Keywords: mid-infrared laser, antimonide laser, type-II quantum well

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