

Tunable, single-frequency, diode-pumped 2.3 μ m VECSEL

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Abstract: We report high-performance single-frequency operation of a directly diode-pumped GaSb-based vertical-external-cavity surface-emitting laser (VECSEL) at 2.3 μ m. Tunability of 70nm and a maximum single frequency output of 0.68W is demonstrated.

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OCIS codes: (140.3580) Lasers, solid-state; (140.3070) Infrared and far-infrared lasers; (140.3570) Lasers, single-mode.

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1. Introduction

Versatile, high-power mid-IR laser sources are vital for emerging applications in gas sensing, communications, and security. The vertical-external-cavity surface-emitting laser (VECSEL) [1] is ideally suited to these applications: it combines high power with high beam quality; provides the potential to engineer the semiconductor gain structure; and permits added

functionality via the external cavity. Currently the majority of research into this novel laser format has concentrated on 1-1.5 μm [2-5], more recently this has been extended to 0.6 – 2.3 μm [6-11]. The extension of the high-power VECSEL demonstrations to the mid-IR region has been facilitated by III-Sb technology [7-11] and effective thermal management techniques, demonstrating, in particular, emission with more than 1W output powers at 2.3 [7,10] and 2.0 μm [11].

In this paper, we report the single longitudinal mode (SLM) operation of a GaInAsSb-based optically pumped VECSEL at 2.35 μm with output powers greater than 0.5W. Single frequency operation over a broad tuning range of 70nm is achieved and preliminary active stabilization locked the laser linewidth below 4MHz.

2. Device structure

The active element of the laser consists of an optically pumped quaternary GaInAsSb/AlGaAsSb gain region and a high quality, high reflectivity (>99.9%) 21.5 GaSb/AlAsSb mirror-pair distributed Bragg reflector (DBR), grown on a GaSb substrate. A schematic of the resonant VECSEL structure is shown in Fig. 1. The active region contains 9, 10nm thick compressively strained (1.5%) GaInAsSb quantum wells, separated by pump absorbing AlGaAsSb barrier regions. The active region is designed to make use of resonant periodic gain (RPG) [12] effects where groups of wells (3,3,3) are placed at antinodes of the intracavity standing wave field, giving a factor of 2 gain enhancement at the design wavelength. The structure is completed with a non-absorbing AlGaAsSb window layer to prevent carrier diffusion and recombination at the device surface, and a thin GaSb cap to prevent oxidation of the aluminum-rich window layer. More detailed analyses of the design of long wavelength VECSEL devices are reported elsewhere [7,11].

GaSb	Cap	
$\text{Al}_{0.85}\text{Ga}_{0.15}\text{As}_{0.06}\text{Sb}_{0.94}$	Window	
$\text{Al}_{0.30}\text{Ga}_{0.70}\text{As}_{0.02}\text{Sb}_{0.98}$	Barrier	
$\text{Ga}_{0.64}\text{In}_{0.36}\text{As}_{0.10}\text{Sb}_{0.90}$	10nm q-well	} x3
$\text{Al}_{0.30}\text{Ga}_{0.70}\text{As}_{0.02}\text{Sb}_{0.98}$	Barrier	
$\text{Ga}_{0.64}\text{In}_{0.36}\text{As}_{0.10}\text{Sb}_{0.90}$	10nm q-well	
$\text{Al}_{0.30}\text{Ga}_{0.70}\text{As}_{0.02}\text{Sb}_{0.98}$	Barrier	
$\text{Ga}_{0.64}\text{In}_{0.36}\text{As}_{0.10}\text{Sb}_{0.90}$	10nm q-well	
$\text{Al}_{0.30}\text{Ga}_{0.70}\text{As}_{0.02}\text{Sb}_{0.98}$	Barrier	
$\text{AlAs}_{0.08}\text{Sb}_{0.92}$	173.7 nm	} x21
GaSb	140.5 nm	
$\text{AlAs}_{0.08}\text{Sb}_{0.92}$	173.7 nm	
GaSb	Substrate	

Fig. 1. Schematic of the device structure showing the key constituent elements.

Figure 2 shows the measured reflectivity profile of the structure with the characteristic Fabry-Perot (F-P) resonance caused by sub-cavity established between the DBR mirror and the front semiconductor/air interface. The figure also includes the unfiltered, or edge, photoluminescence (PL) emission from the active region, and the backscattered PL filtered by the sub-cavity resonance.

Figure 2 indicates that the structure is not completely optimized for high power operation: the PL and resonance features will shift to longer wavelengths at different rates with increased heating due to pumping (typically $\sim 1.25\text{nm}/^\circ\text{C}$ and $0.25\text{nm}/^\circ\text{C}$ respectively in this material system) therefore increasing the relative separation and rapidly decreasing the gain at the resonance. For optimized device performance, the peak of the edge PL emission should lie below the resonance feature at room temperature (in wavelength terms) so that as the device is

heated by the pump, the maximum gain will shift on to the resonance. This effect accounts for the need to cool the device to achieve high power (>0.5W) operation. Future device optimization will permit higher room-temperature output powers in the 2 to 2.5 μm range

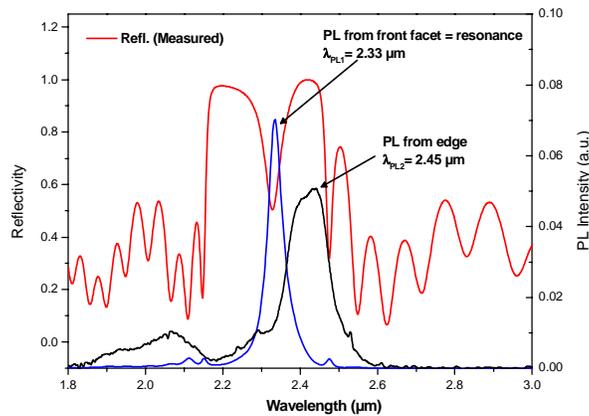


Fig. 2. Measured room-temperature static characteristics of the VECSEL structure showing the reflectivity (red), the backscattered PL (blue) and the edge PL (black)..

3. Experimental setup

The typical arrangement of the 2-mirror VECSEL cavity used in the initial experiments is shown in Fig. 3.

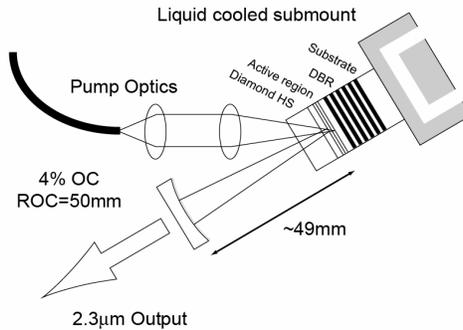


Fig. 3. Schematic of the typical 2-mirror VECSEL configuration. (HS: heatspreader)

The pump light is provided by a 15W commercial (LIMO GmbH) 100 μm -core fibre-coupled, InGaAs diode laser at 980nm. The pump light is coupled into the active region via collimating and focusing lenses with focal lengths of 14.5mm and 11mm respectively, resulting in a near-Gaussian beam profile at the pump focus. Translation of the pump optics allowed the pump spot diameter to be readily varied between 80 and 400 μm ; however, for the results presented here the pump radius was typically around 100 μm .

In order to efficiently remove heat from the active region, the top surface of the semiconductor structure was capillary bonded to a \sim 230 μm thick single-crystal, natural diamond heatspreading window [4]. This ensemble was then clamped to a liquid-cooled brass mount. The transparent heatspreader effectively bypasses the large thermal impedances of the DBR and substrate [13] – significantly ameliorating the thermal effects that have limited the performance of GaSb VECSELs [8,9] and enabling high power operation. This active element formed one end of the resonator. Initially, a 50mm radius of curvature (ROC), 4% output coupling mirror was employed to complete a short, near-hemispherical ($l=49\text{mm}$), 2-mirror laser resonator. For the tuning and locking experiments, a 100mm ROC high reflector (HR)

mirror and a flat 2 or 3% output coupling (OC) mirror were used in a 3-mirror cavity, with typical short and long arm lengths of 55mm and 300mm respectively.

4. Results

With the mount temperature held at 15°C, the maximum output power was 350mW. Figure 4 shows the power transfer characteristic with the mount cooled to -15°C, giving a maximum – pump power limited – output of 860mW. The transverse mode was near diffraction limited in both cases ($M^2 < 1.1$).

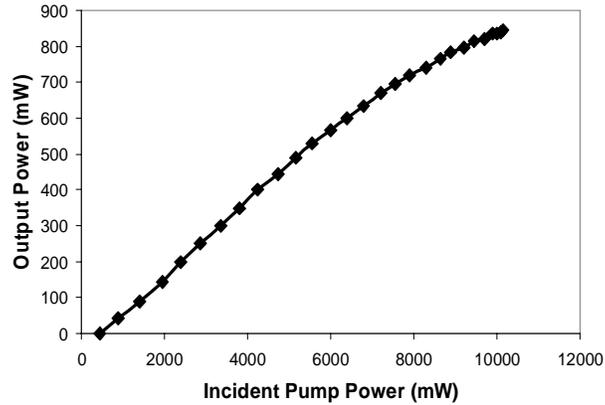


Fig. 4. CW power transfer characteristic of the Mid-IR VECSEL cooled to -15°C.

When not optimally aligned, the output exhibited relatively large intensity noise. With the pump and cavity mode overlap optimized, there was an abrupt reduction in intensity noise, an increase in power and a corresponding spectral enhancement (see Fig. 5).

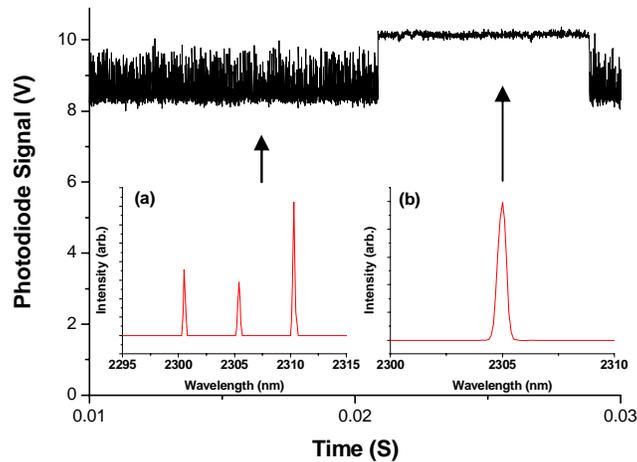


Fig. 5. Typical transition behavior between free-running (a) multi-mode and (b) SLM operation (see inset spectra) with careful cavity alignment.

Figure 5(a) shows a typical spectrum for non optimal alignment, the 5nm spacing between the peaks is consistent with the free spectral range of the diamond heatspreader. Figure 5(b) shows the spectral enhancement to operation to within one of these diamond etalon modes and is resolution limited (0.44nm) by the grating spectrometer (Jobin Yvon HR460). The obvious reduction in intensity noise indicates a sudden reduction in mode competition (an effect inversely proportional to the number of competing longitudinal modes) and the transition to a

stable operating regime which is able to extract gain from the active region more efficiently. Coincident with this spectral enhancement and suppression of laser intensity noise, strong interference fringes became visible across the output image on a camera that was being used to observe the output beam shape. Together these effects indicated a shift to single longitudinal mode (SLM) operation. Careful spatial mode control – by the precise alignment of the cavity and pump focusing – stabilized this enhanced mode of operation and allowed free-running, SLM operation of the laser [see Fig. 5(b)].

SLM operation was quite robust, despite the absence of active stabilization – running continuously for many minutes. Single frequency operation was confirmed using a scanning Fabry-Perot etalon with a free spectral range of $\sim 12\text{GHz}$ (cavity mode spacing $\sim 3\text{GHz}$, see Fig. 6). Free-running single frequency operation was observed at output powers up to 680mW at -15°C : an increase of more than two orders of magnitude over that previously reported [9].

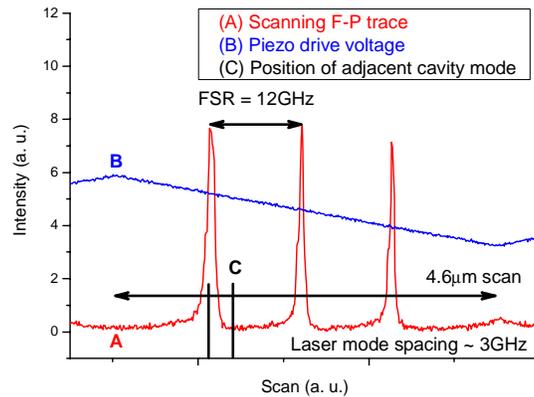


Fig. 6. Trace from a scanning Fabry-Perot etalon with a free spectral range (FSR) of approximately 12GHz showing the piezoelectric drive voltage (B) and the relative position of the adjacent longitudinal cavity mode (C).

The use of a longer 3-mirror cavity readily permitted the inclusion of a 2mm thick quartz birefringent filter (BRF). By rotating the BRF, the laser could be readily tuned over 70nm from 2260nm to 2335nm (limited by the decreasing reflectivity of the external cavity optics at the upper wavelength end). A typical tuning characteristic is shown in Fig. 8. SLM operation across the entire tuning range of the laser could be obtained by cavity realignment (see Fig. 7).

Single frequency operation could be considered a natural state of operation for this type of laser. The suppression of spatial hole-burning and gain narrowing from the distributed gain (RPG), plus the short length of the active region, encourage operation on a single longitudinal mode. The thin diamond etalon also filters the device gain, with the longer wavelength of operation giving a larger mode-spacing. Single frequency operation requires oscillation on a single polarization mode and a single transverse mode: a single polarization is encouraged by the elliptical pump spot in the active region (due to off-axis pumping) – note that care must be taken to avoid the deleterious birefringent effects often associated with natural diamond heatspreaders [14]; careful matching of the pump and laser modes encourages single transverse mode oscillation, since re-absorption in unpumped areas discourages higher order transverse modes. Precise cavity alignment is required to achieve this mode matching and ensure single frequency oscillation (see Fig. 5).

The output coupler of the 3-mirror single frequency laser cavity was then fixed to a piezoelectric transducer coupled to a simple feedback circuit (see Fig. 8). The scanning F-P cavity was used as a reference cavity where the length was fixed to give a transmission of 50% , i.e. on the edge of the SLM feature. The feedback circuit generated an error signal which was amplified and applied to the piezo actuator to lock the cavity length and narrow the

laser linewidth. The amplitude of the error signal confirmed that the SLM linewidth was narrowed to $<4\text{MHz}$. This was limited by the short ($l \sim 12.5\text{mm}$) F-P reference cavity and the associated electronics. No attempt was made to stabilize the environment around the laser cavity. Future experiments will focus on improvements in the cavity stabilization and filtering, and an improved reference cavity, which should permit the active stabilization of the linewidth to a few kHz; for many applications however, the achieved linewidth would already be sufficient.

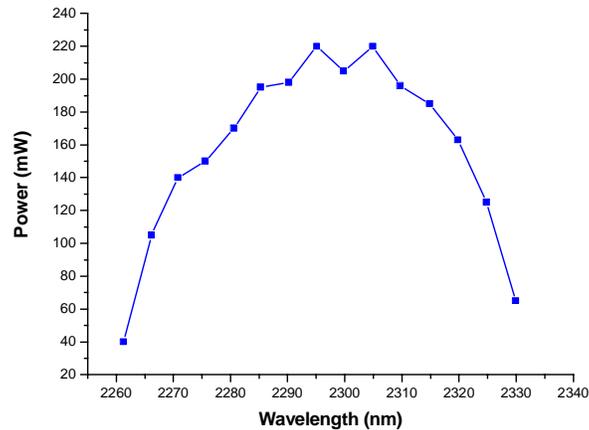


Fig. 7. Typical tuning characteristic obtained at moderate output powers. Each point was optimized for stable SLM operation.

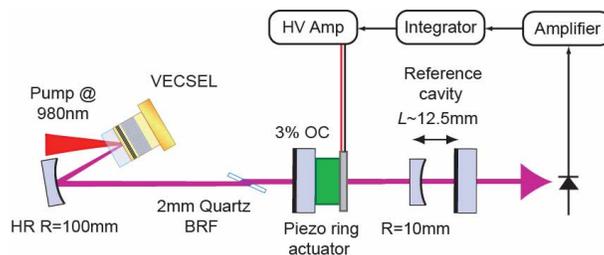


Fig. 8. Schematic of the cavity arrangement and electronics used for the locking and line narrowing of the single frequency VECSEL operation.

5. Conclusion

We have shown the enhanced operation of a high power CW (0.86W), broadly tunable ($\sim 70\text{nm}$), single frequency (0.68W), narrow linewidth ($<4\text{MHz}$), GaSb-based mid-IR VECSEL, emphasizing the versatility of this laser format. The demonstration of such a high-performance VECSEL in the 2-2.5 μm region is a significant step towards a versatile, low-cost solution for a wide range of sensing, imaging and diagnostic applications. We believe that there is great potential for higher powers, narrower linewidths and broader tunability from this material system in this wavelength region.

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