2.34 µm electrically-pumped VECSEL with buried tunnel junction

Antti Härkönen*[a], Alexander Bachmann[b], Shamsul Arafin[b], Kimmo Haring[a], Jukka Viheriälä[a], Mircea Guina[a], and Markus-Christian Amann[b]

[a]Optoelectronics Research Centre, Tampere University of Technology, Korkeakoulunkatu 3, FI-33720 Tampere, Finland +358-(0)3-8490002;

[b]Walter Schottky Institut, Technische Universität München, Am Coulombwall 3, D-85748 Garching, Germany +49-(0)89-289-12788

ABSTRACT

Mid-infrared semiconductor laser are highly attractive sources for environmental monitoring since the spectral fingerprints of many environmentally important gases are located in the 2–3.3 µm wavelength regime accessible by gallium-antimonide technology. Here an electrically-pumped vertical-external-cavity surface-emitting laser (EP-VECSEL) was realized at 2.34 µm wavelength, using a gain mirror based on the GaSb material system. The gain mirror was grown by molecular beam epitaxy on an n-type GaSb substrate and it included a distributed Bragg reflector made of 24-pairs of AlAsSb/GaSb layers, and a gain region with 5 GaInAsSb quantum wells placed in a 3-λ thick micro-cavity. A structured buried tunnel junction (BTJ) with subsequent overgrowth was used in order to obtain efficient current confinement, reduced optical losses and increased electrical conductivity. Different components were tested with aperture sizes varying from 30 µm to 90 µm. Pulsed lasing was obtained with all tested components at 15 °C mount temperature. We obtained a maximum peak power of 1.5 mW at wavelength of 2.34 µm.

Keywords: Semiconductor lasers, buried tunnel junction, electrically-pumped VECSELs, GaSb, gallium-antimonide lasers, external cavity lasers, vertical cavity lasers, mid-infrared lasers.

1. INTRODUCTION

Vertical-cavity surface-emitting diode lasers, such as electrically-pumped VCSELs and VECSELs possess many advantageous features such as high beam quality, wavelength flexibility, small footprint and convenient pumping scheme. Due to broad gain spectrum these lasers can be wavelength tuned easily; VCSELs by current and temperature and VECSELs with a spectrally selective filter placed inside the laser resonator. The VCSELs have an ultra-compact monolithic design that is mass producible and inexpensive, whereas the VECSELs require external parts and active alignment, making the laser more complicated. However, the maximum single-mode optical power obtained from VCSELs is typically limited to mW level due to small gain volume. The VECSEL architecture, on the other hand, offers a way for power scaling by increasing the pumped gain area, while single-mode operation is forced by the external cavity mirrors.

A significant effort has been made previously to develop the EP-VECSEL technology for the blue and green by frequency-doubling ~970 nm and ~1050 nm fundamental infrared emission [2]. Work has been also carried out to develop these sources for the wavelengths of 850 nm and 1550 nm [3,4]. Output power as high as 500 mW has been reported previously in single-mode operation and 1 W in multimode operation at wavelength near 980 nm [5]. The tuning range of VECSELs is also large; previously we have demonstrated lasing in ~150 nm band in optically pumped devices operating near 2 µm [1]. The external cavity design allows also use of intra-cavity optical elements such as nonlinear frequency-conversion crystals or saturable absorber mirrors.

Because of their favorable properties VECSELs are highly interesting light sources for a number of applications including visible light generation, substitution of ion lasers, life-sciences, etc.

*antti.harkonen@tut.fi; phone +358 40 198 1059; fax +358 3 3115 3400

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Because of the large gain spectrum VECSELs are potential sources for tunable diode laser absorption spectroscopy (TDLAS) and intra-cavity laser absorption spectroscopy (ICLAS) [6]. In the latter application the high intra-cavity intensity of a laser is used for enhancing the accuracy of absorption spectrum measurements. Both applications are particularly interesting in the mid-infrared wavelength region where many environmentally important gases, such as CH_4, CO_2 and CO for example, have strong absorption lines. The targeted wavelength range is accessible by GaSb material system but the development of surface-emitting GaSb-based diode lasers has been hindered by technical problems related to optical losses in thick p-doped layers and to provide sufficient current confinement in the structure. Lately, a significant progress was made in the field with the demonstration of VCSELs with a buried tunnel junction emitting between 2.3 and 2.6 µm, produced by etching and an over-growth step [7,8]. The function of the tunnel junction is to provide a current aperture for carrier confinement. It also allows the substitution of p-doped layers to n-doped ones reducing optical losses. Essentially this technology has enabled one to overcome the technical challenges that have previously hindered the GaSb-based VCSEL development. In this work we demonstrate a vertical external-cavity surface-emitting diode laser utilizing similar BTJ technology as used earlier in VCSELs.

2. GAIN MIRROR DESIGN AND FABRICATION

The key element to the laser is the epitaxially grown semiconductor gain mirror with the buried tunnel junction. The gain mirror is formed of a distributed Bragg reflector, an active region, a buried tunnel junction and a current spreading overgrowth layer as shown schematically in Figure 1. The epitaxial layers were grown by molecular beam epitaxy (MBE).

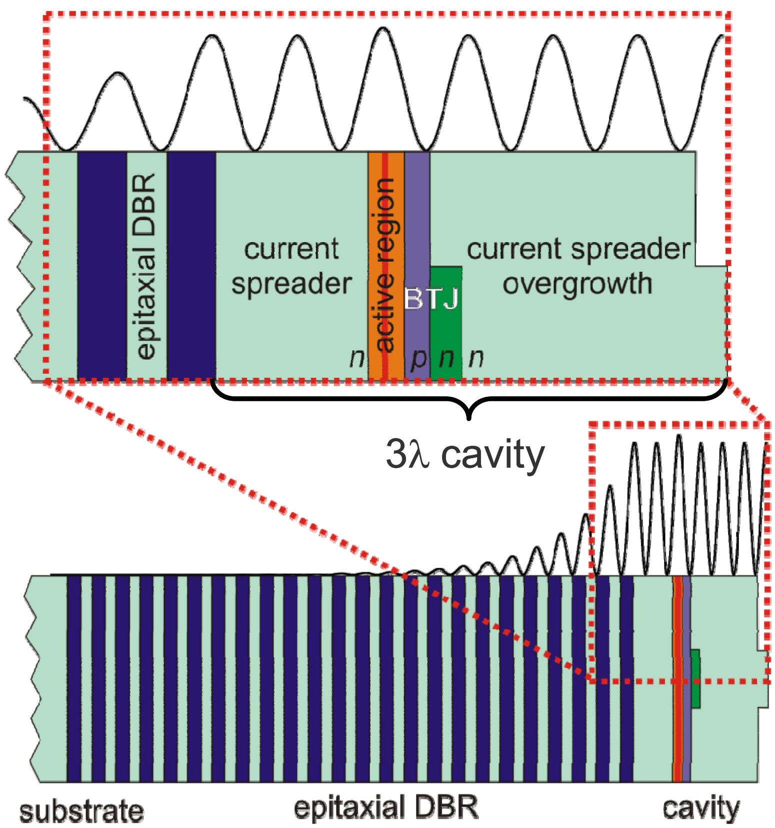


Figure 1. Field distribution in the GaSb-based gain mirror. The structure consists of an epitaxial GaSb / AlAsSb mirror and a 3λ-thick layer structure on top including the active region in an antinode and the BTJ in a node of the optical field.

The Bragg reflector consists of 24-pairs of ¼-λ thick n-doped AlAsSb/GaSb layers grown on an n-doped GaSb substrate. The mirror structure was followed by an n-type GaSb current spreading layer and an active region containing 5 $GaIn_{0.37}As_{0.11}Sb$ quantum wells. The tunnel junction was formed between a highly doped p^+-GaSb layer and an n^+-InAsSb grown on top of the active region as shown in Figure 2. The lateral current confining feature was fabricated by a lithographic step followed by selective etching, after which only selected parts of the n^+-InAsSb layer remained on the wafer forming a current aperture. The structure was concluded with an overgrowth of an n-type current spreading layer and a contact layer. The components were processed on the wafer by etching a mesa structure and fabricating necessary passivation layers and metal contacts as shown in Figure 3.

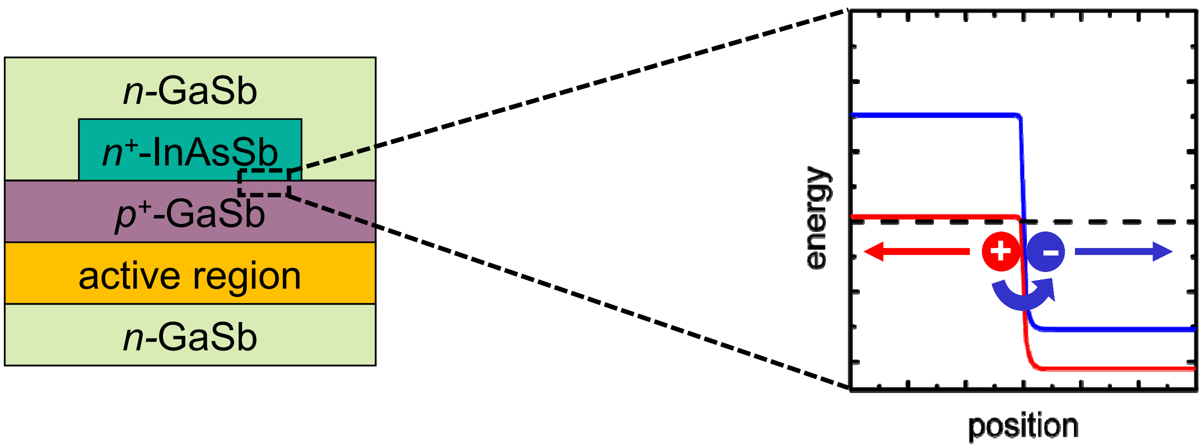


Figure 2. Schematic structure of the tunnel junction serving as a current aperture, and the band diagram of the p^+-GaSb / n^+-InAsSb heterojunction, where the tunneling occurs. On the etched outer parts of the aperture, a blocking p^+- / n-GaSb structure is formed.

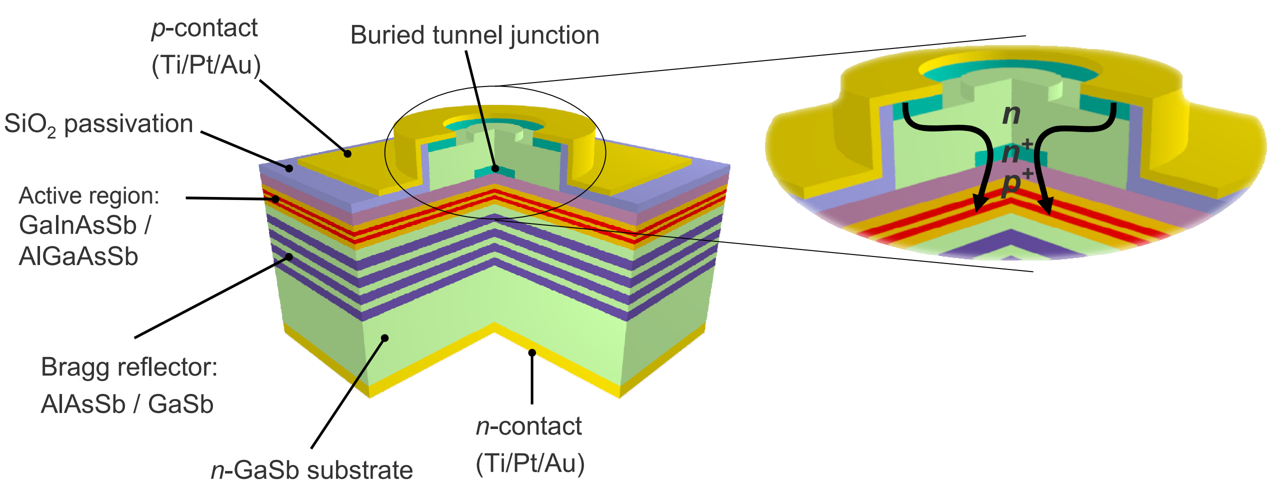


Figure 3. Schematic structure of the gain mirror. Carriers are injected into the active region through the top and bottom contacts. The carriers are confined to the center of the device by means of the buried tunnel junction.

The reflectivity spectrum and photoluminescence (PL) were measured from the as-grown wafer and are shown in Figure 4. The stopband of the Bragg reflector spanned nearly 300 nm with a resonance dip near 2.35 µm. The photoluminescence maximum is slightly detuned from the resonance towards the shorter wavelengths to account for thermal red shift under operation.

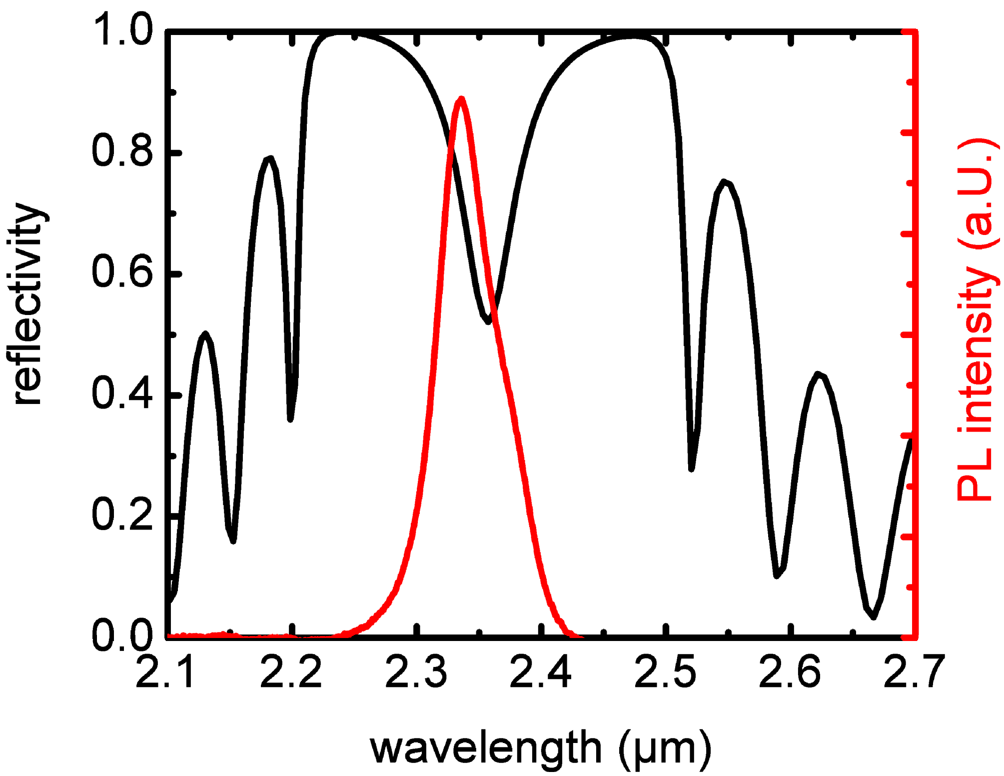


Figure 4. Reflectance spectrum and photoluminescence curve measured from the sample.

3. LASER CHARACTERIZATION

All measured laser components were processed on the same chip and had an aperture diameter varying from 30 µm to 90 µm. The chip was bonded on a copper heat sink and the components were electrically contacted using a prober (Figure 5).

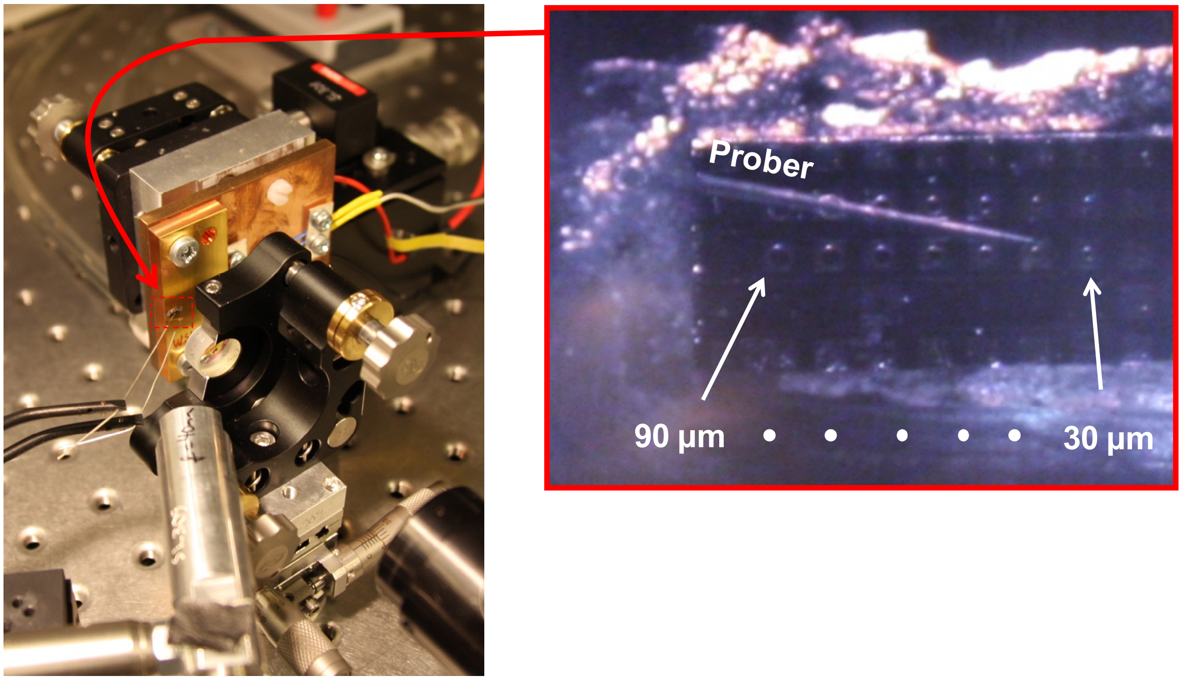


Figure 5. *Left:* A photograph of the laser. *Right:* Soldered semiconductor chip with different components having aperture diameters varying from 30 µm to 90 µm. The prober is contacted to the 40 µm device.

An I-shaped laser cavity was formed between the gain mirror and a curved output coupler with 98–99% reflectivity (Figure 6). With the two smallest components (30 µm and 40 µm) we used an output coupler with radius of curvature RoC=15 mm. A mirror with RoC=25 mm was used with the other components. The lasers were operated close to the stability limit with the cavity length being nearly equal to the radius of the curvature of the external mirror. Pulsed pumping with 1-µs pulse duration and 3% duty cycle was used to avoid excessive heating of the components.

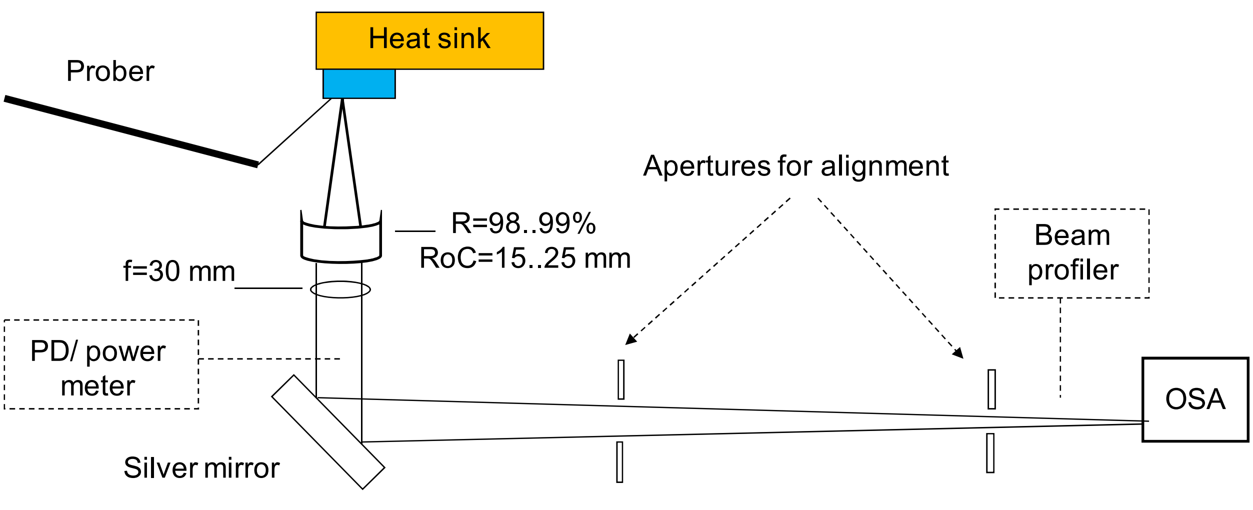


Figure 6. Schematics of the laser characterization setup. PD=Photodiode, OSA=Optical spectrum analyzer

The laser characterization setup, also presented in Figure 6, includes a f=30 mm focusing lens to collect the output light, a photodiode/power meter, a beam steering mirror, a pyroelectric beam profiler camera and an optical spectrum analyzer. The light output characteristics were recorded with a photodiode and the maximum output power was recorded with a power meter. The obtained results are shown in detail in Figure 7. As expected the threshold current increased with increased aperture size, but surprisingly the maximum output powers were very similar for all of the components except the very largest one (90 μm). The highest peak output power of 1.5 mW was measured from the 60 μm component. The 40 μm component was mechanically damaged and was therefore not included in the graph, although lasing was obtained also with this device.

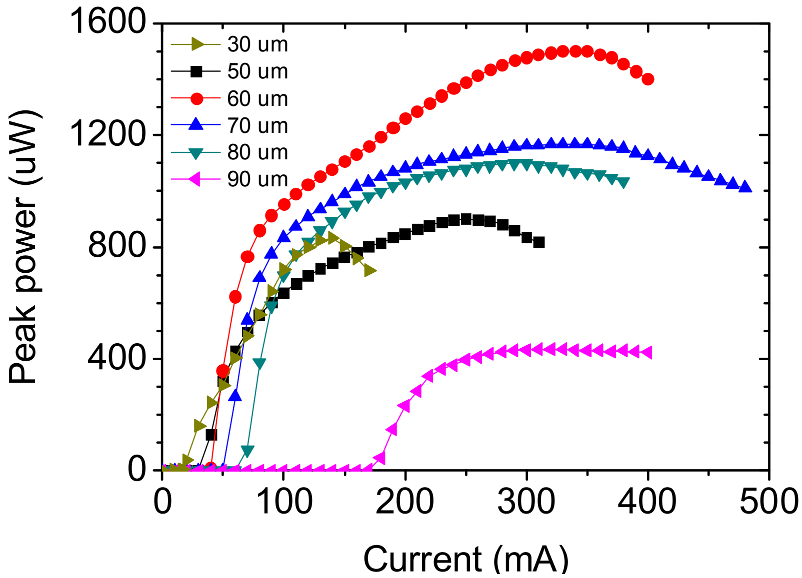
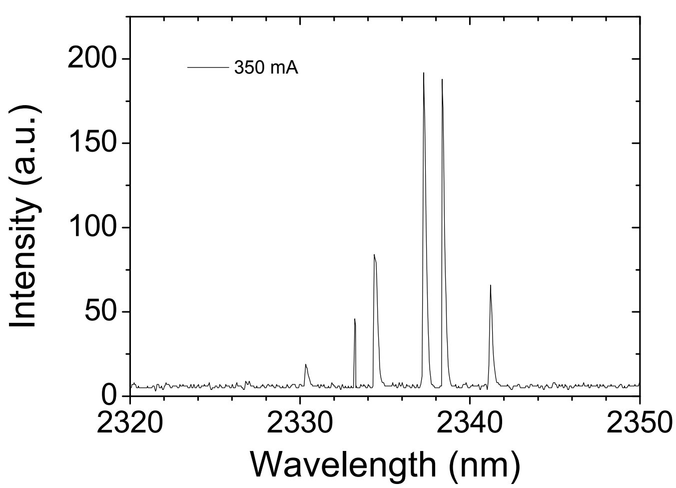


Figure 7. Light output characteristics from different components using 99% reflective output coupler.

The optical spectrum near 2.34 μm was recorded with an APE WaveScan spectrometer and is shown in Figure 8 along with the beam profile recorded with the pyroelectric camera.



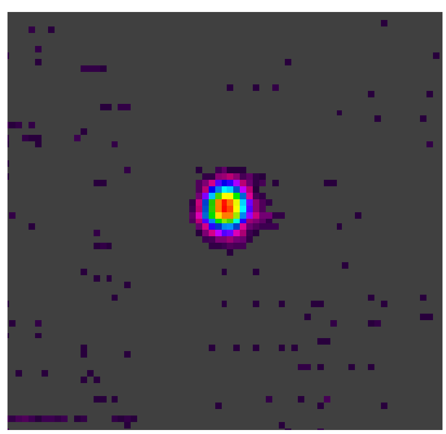


Figure 8. Left: Optical spectrum from the 60 μm component at 350 mA current. *Right:* Beam profile of the 60 μm component measured with a pyroelectric camera. Exposure time 10 frames.

4. CONCLUSION

The results obtained in this work show that buried tunnel junction GaSb technology can be used for realizing an EP-VECSEL at wavelength near 2.34 µm. In the future the demonstrated laser scheme could be attractive for applications requiring large gain bandwidth and wavelength tunability. Such applications are for example tunable diode laser spectroscopy and intracavity laser absorption spectroscopy. The peak output power of the devices tested here was limited to about 1.5 mW in pulsed operation. The power could be limited by thermal effects and it is likely that better results would be obtained by using more advanced thermal management techniques, such as diamond heat spreader element or flip-chip processing. Use of wire bonded components would also be advantageous. The future work should also include tests of wavelength tuning by using an intracavity filter.

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