Jet Propulsion Laboratory
California Institute of Technology

First Demonstration of Single-Mode Distributed Feedback Type-I GaSb Cascade Diode Laser Emitting near 2.9 µm

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Outlines

- Importance of OH radical measurements
- GaSb-based type-I cascade diode laser
- Fabrication of laterally-coupled distributed feedback (LC-DFB) GaSb-based type-I cascade diode laser
- Performances of Fabry-Perot and LC-DFB type-I cascade diode laser
- Conclusion

Importance of OH radical measurements

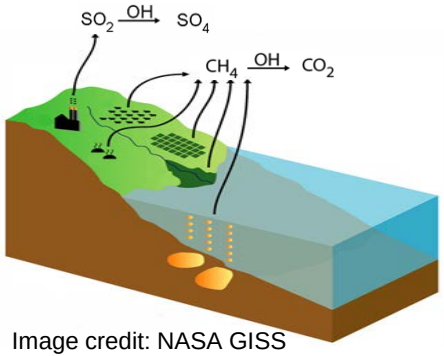
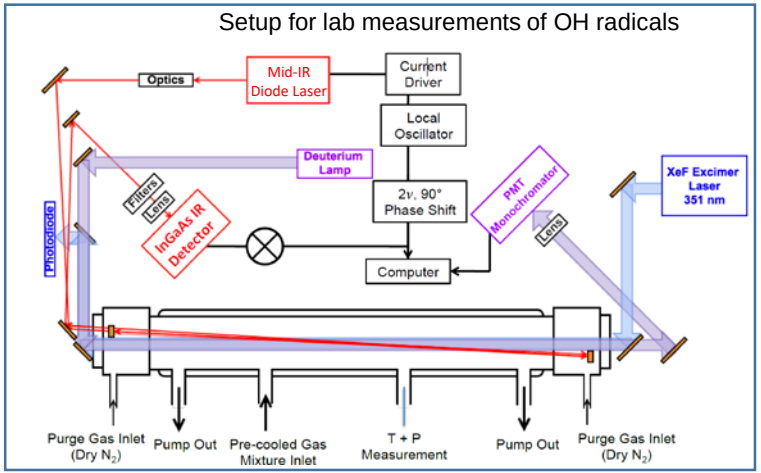


Image credit: NASA GISS



- OH radical interacts strongly with ozone and greenhouse gases.
- In the remote atmosphere, acetone ($CH_3C(O)CH_3$) is among the most abundant oxygenated organic compounds, with surface mixing ratios ranging from 5000 to 2000 pptv.
  - Acetone oxidation occurs either through photolysis or reaction with OH radicals.
  - Under tropospheric conditions, the reaction with OH occurs twice as fast as photolysis and produces the acetonylperoxy radical.

<u>$CH_3C(O)CH_3$ Oxidation – reaction with OH</u>

$CH_3C(O)CH_3 + OH \rightarrow H_2O + CH_3C(O)CH_2$

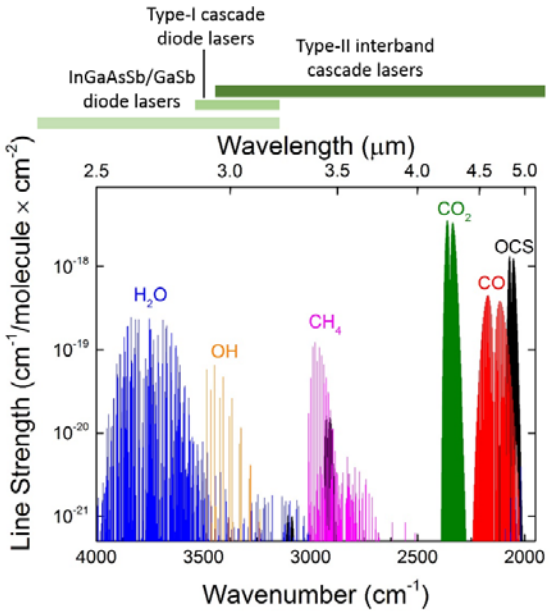
$CH_3C(O)CH_2 + O_2 + M \rightarrow CH_3C(O)CH_2O_2 + M$

<u>$HO_2 + CH_3C(O)CH_2O_2$ reaction</u>

$HO_2 + CH_3C(O)CH_2O_2 \rightarrow CH_3C(O)O_2 + CH_2O + OH$

- Laser-induced fluorescence (LIF) has been used extensively but measures lifetime and requires multi-stages UV laser systems which are large, expensive, and power-hungry.
- Mid-IR semiconductor lasers offers potential break-through in OH measurements with low mass, high output power, and reliability.

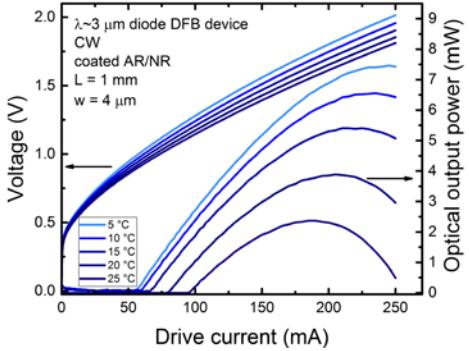
OH radicals measurements using absorption spectroscopy



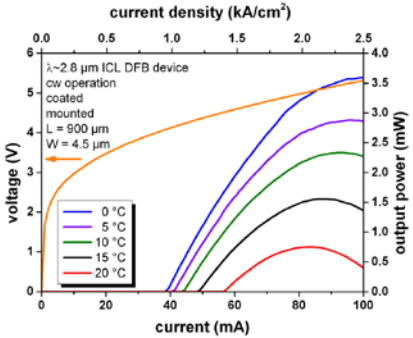
OH targeted wavelength ~2.9 µm

OH absorption lines in the 3-µm regime can be targeted using different laser structures

- <u>InGaAsSb/AlInGaAsSb diode</u>
  - Viability proven in the 2- to 3-µm regime.
  - Professor Gregory Belenky's group from SUNY at Stony Brook has fabricated diode with emission above 3-µm.
  - James Gupta's group from National Research Council of Canada has developed diode with emission up to 3.3-µm.
  - Losses due to Auger recombination and insufficient hole confinement become important at wavelengths close to 3-µm.
- <u>GaSb-based type-II interband cascade lasers</u>
  - Developed by Rui Q. Yang
  - Multiple quantum well, and electron injector stages to emit multiple photon.
  - Jerry Meyer's group at Naval Research Lab (NRL) has been leading the development of ICLs in the 3- to 5-µm regime
  - Emission possible but low efficiency at wavelength below 3-µm



Device fabricated at JPL, growth at NRC

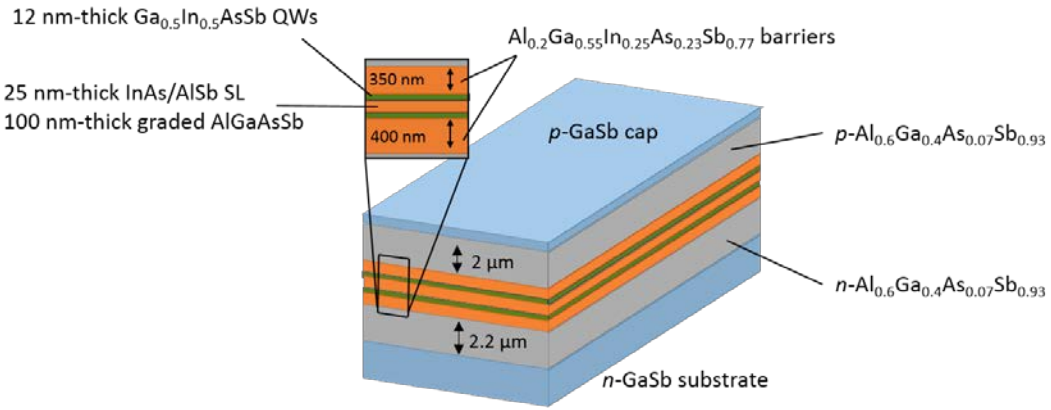


Scheuermann *et al.*, Appl. Phys. Lett 106, 161103 (2015)

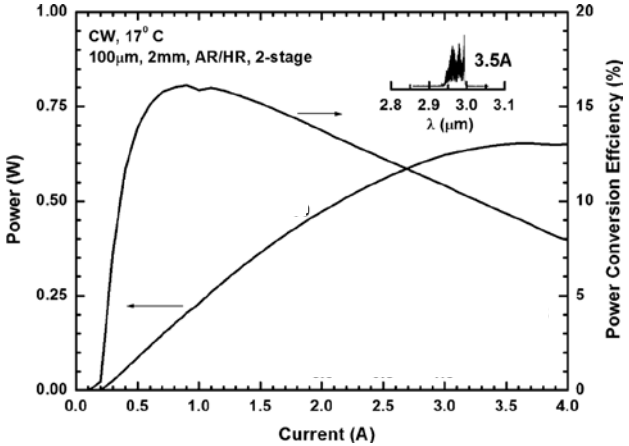
GaSb-based type-I cascade diode laser

- GaSb-based type-I cascade diode laser
  - Developed from Gregory Belenky and Leon Shterengas' group at State University of New York at Stony Brook for **high output power around 3-µm**
  - Minimize the QW threshold carrier concentration through improvement of the optical confinement factor
  - Increases device internal efficiency

Type-I cascade diode laser structure

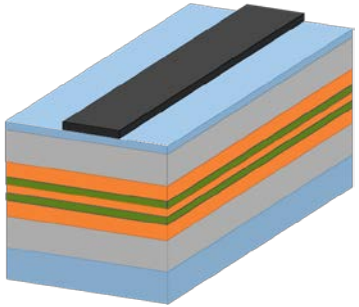


Broad area type-I cascade diode laser

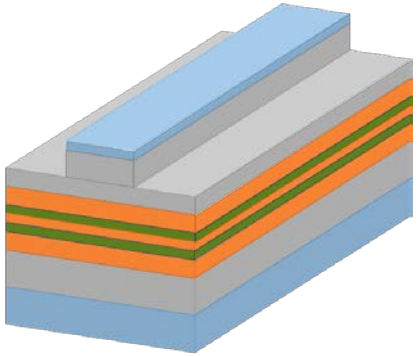


Shterengas *et al.*, Appl. Phys. Lett. 105, 161112 (2014)

Laterally coupled DFB GaSb-based type-I cascade diode laser fabrication steps

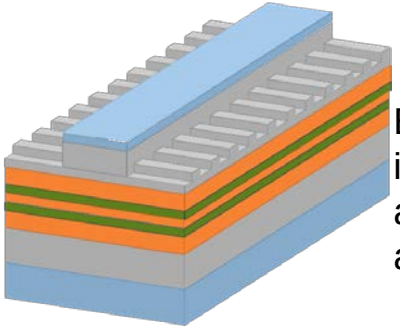


Defining ridge waveguide with optical lithography

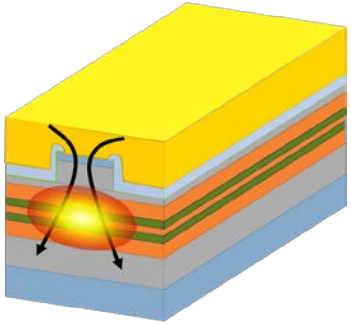


Ridge waveguide etched ~2-µm deep using a BCl_3/Cl_2 plasma

E-beam lithography

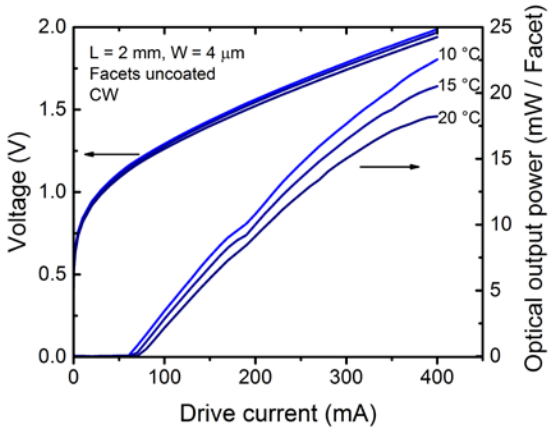


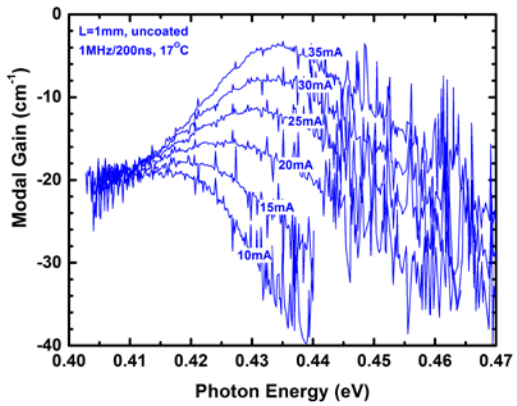
Etching of second order index-coupled DFB with a pitch of 825- or 826-nm and a duty cycle of ~30%



Deposition of SiN_x ~400-nm thick followed by a Au top contact ~4-µm thick electroplated on top of the devices

Fabry-Perot GaSb-based type-I cascade diode





Optical power – Current – Voltage (LIV) measurements

$I_{threshold}$: ~75 mA (0.94 kA/cm^2)
Optical power : more than 22 mW at 10 °C and 18 mW at 20 °C
Voltage across the device: below 2 V

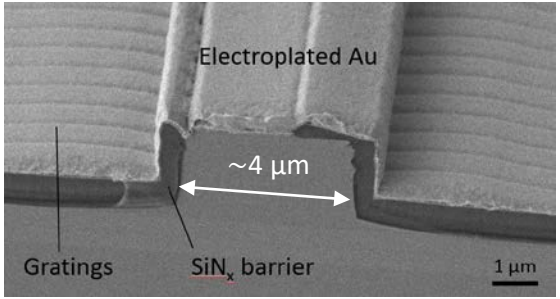
Hakki-Paoli optical gain measurements

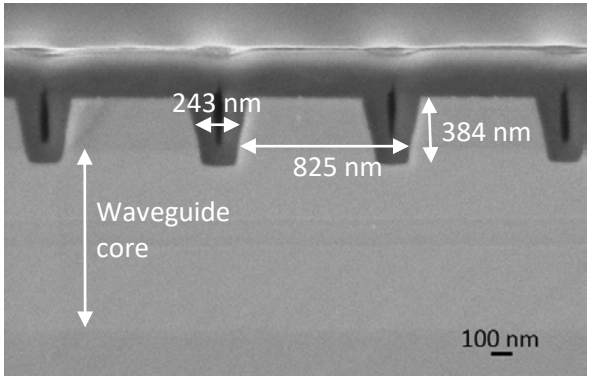
$$g(\lambda) = -\frac{1}{L}\left(\frac{\sqrt{P_{max}/P_{min}}+1}{\sqrt{P_{max}/P_{min}}-1}\right), \text{ Mirror losses} = \frac{\ln(R)}{L}$$

Total loss : 19 – 20 cm^{-1}
Internal loss : 7 – 8 cm^{-1}

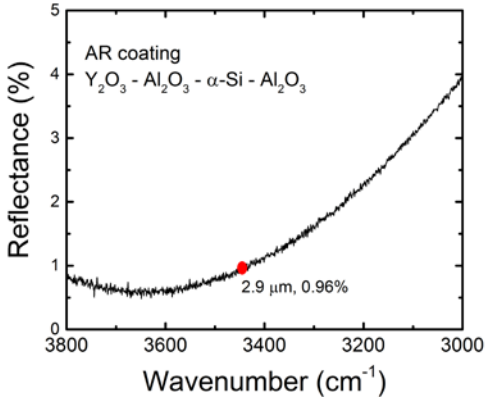
Similar to devices with 80% Al content in cladding
(Liang et al., IEEE Photon. Techn. Lett. 27 (2015))

Laterally coupled DFB GaSb-based type-I cascade diode laser fabrication





- Fabrication of ~4 µm wide ridges, Λ=825 nm and 826 nm, duty cycle ~30%.
- Slight rounding observed where the etched surface meets the ridge sidewall. Ridges limits the solid angle over which the neutral species can reach the surface.
- Gratings do not penetrate into the top barrier close to the ridges, but does far from it.
- Grating coupling coefficient calculated to be ~13 cm^{-1}

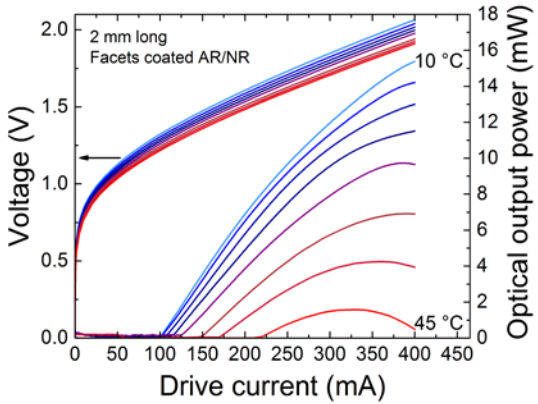


Anti-reflectivity coating on emitting facet, neutral-reflectivity for passivation on back facet

AR coating: measured reflectivity of ~1%

Performances

Optical power – Current – Voltage (LIV) measurements



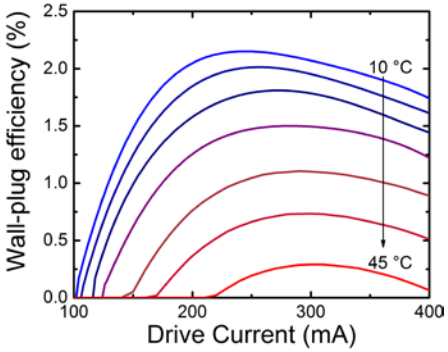
$I_{threshold}$: from 100 mA (1.25 kA/cm^2) at 10 °C up to 220 mA (2.75 kA/cm^2) at 45 °C

Optical power : more than 15 mW at 10 °C and **13 mW at 20 °C**

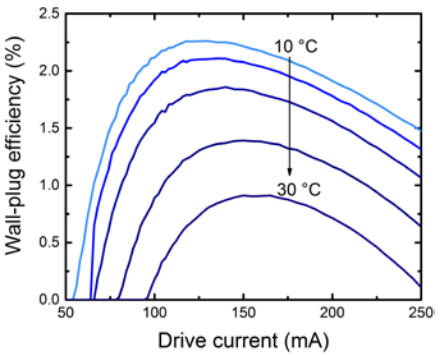
Voltage across the device: below 2 V

Wall-plug efficiency measurements

2-mm-long LC-DFB type-I cascade diode



1-mm-long LC-DFB diode, λ ~ 3 µm



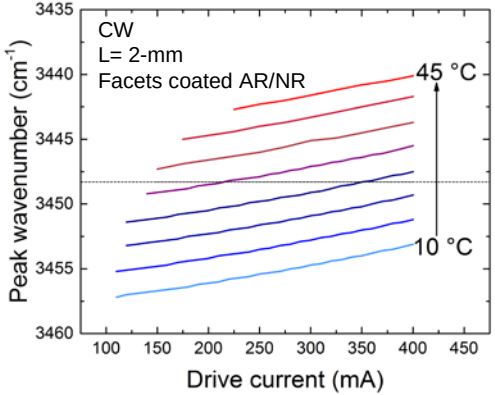
Maximum wall-plug efficiency of 2.2 % at 10 °C

Similar to type-I diodes fabricated previously

Electrical and optical performances for the LC-DFB type-I cascade diode are similar to type-I diodes emitting near 3 µm

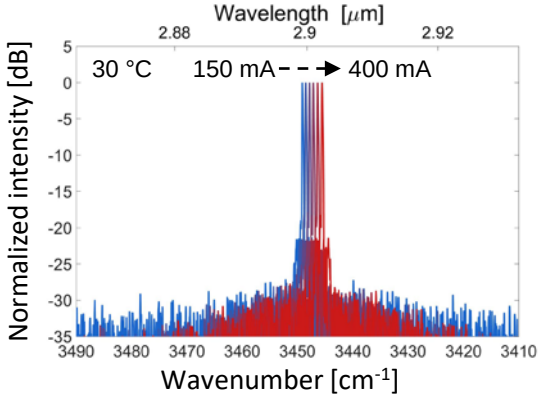
Performances

Spectra characteristics

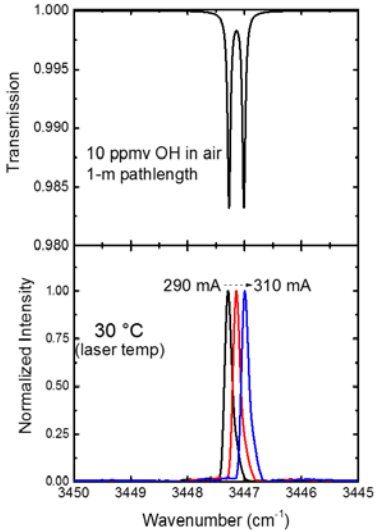


Mode-hop free single-frequency emission over a wide range of current and heat-sink temperature was observed.

Tuning rate of 0.32 nm/K was measured.



The optical spectra measured with a FTIR shows a side-mode suppression ratio (SMRS) over 25 dB.

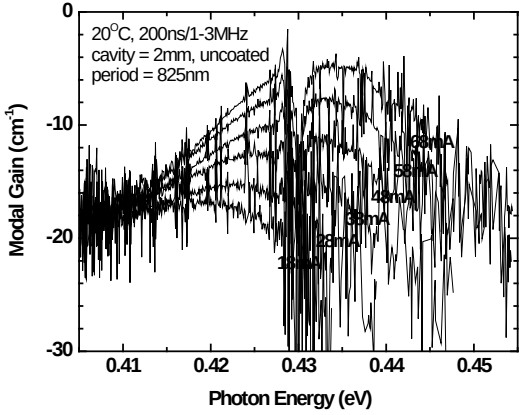


Single-mode device can tune over OH absorption pair lines centered at 3447 cm^{-1} (2.901 µm).

Targeted wavelength is hit in single-mode emission with 8 mW of output power.

Performances

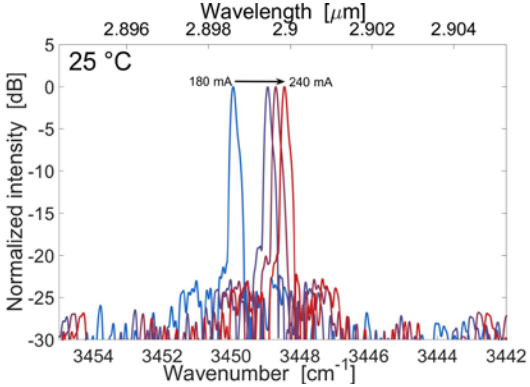
Gain spectra characteristics

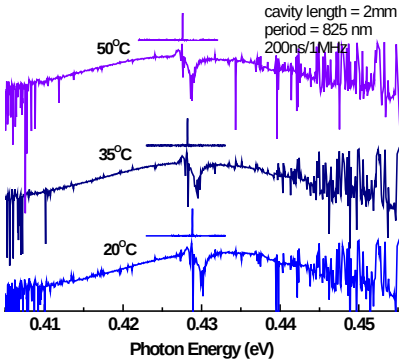


Hakki-Paoli optical gain measurements

Total loss : ~18 cm^{-1} (2-mm-long device)
Internal loss : ~11-12 cm^{-1}

Increase of 3-4 cm^{-1} compare to FP devices





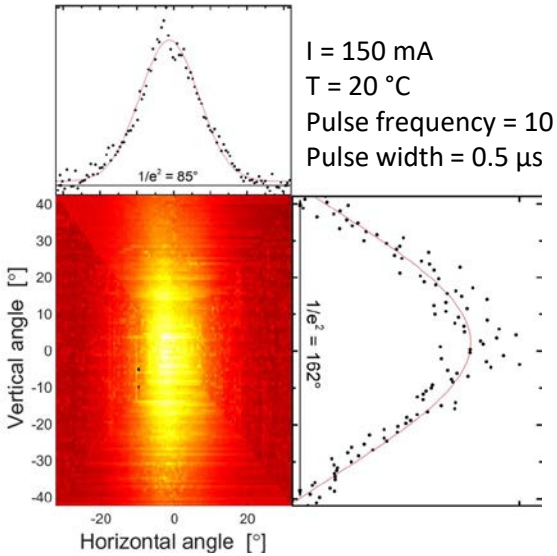
Distortion of gain spectra near 0.43 eV corresponds to grating stopband, which is 5 meV from the max gain.
Gain peak tuning of ~1.23 nm/K

Mode-hop on some device can be present. DFB mode on red side of stop band becomes dominant due to thermal laser gain shift to longer wavelengths with increasing current.

Over 20dB of SMSR after a mode-hop was observed

Performances

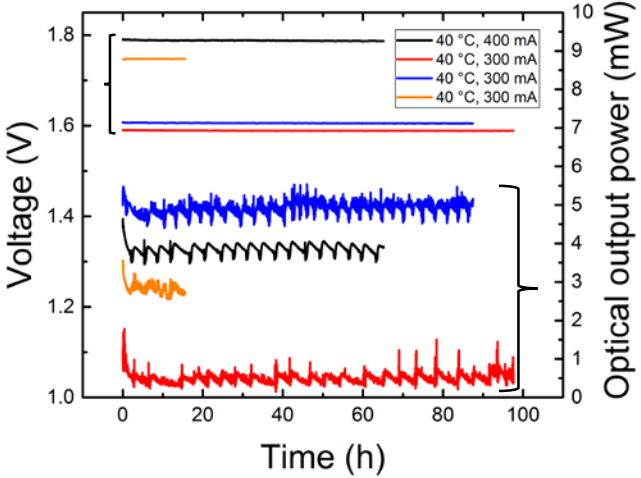
Optical beam divergence



I = 150 mA
T = 20 °C
Pulse frequency = 10 kHz
Pulse width = 0.5 µs

Measured divergence angle of slow-axis to be 85° and fast-axis to be 162° at $1/e^2$

Burn-in measurements

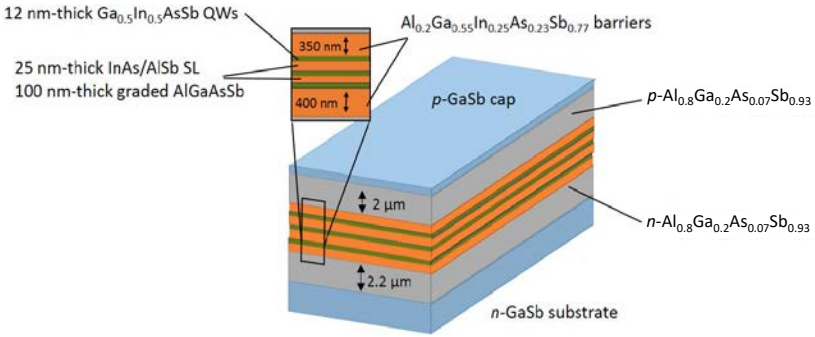


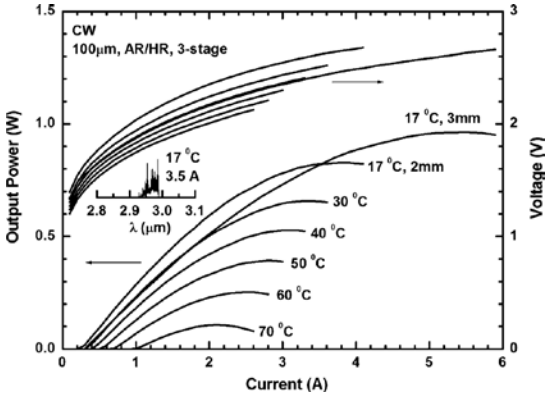
Variations in the optical power are due to the temperature fluctuations in the lab.

No sign of early failures

Future perspectives

Avenue to increase the optical power of LC-DFB devices: 3-stage cascade diode laser





Schterengas *et al.*, Appl. Phys. Lett 105, 161112 (2014)

Broad area devices emitting ~960 mW near 3 µm

Conclusion

- We have fabricated narrow-ridge waveguide LC-DFB type-I cascade diode lasers that emit in single-frequency at 2.9 µm.
- We have measured an optical output power of more than 15 mW and a maximum wall-plug efficiency of 2.2 % at 10 °C.
- The tuning rate was 0.32 nm/K and we observed single-frequency emission over a large range of current and device temperature.
- Internal loss was found to be 7-8 cm^{-1} for Fabry-Perot devices and 11-12 cm^{-1} for LC-DFB devices.
- Fabrication of LC-DFB with higher optical output power within reach.

Acknowledgement

- Departement of ECE at State University of New York at Stony Brook, group of
  - **Takashi Hosoda, Leon Shterengas, and Gregory Belenky**
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  - **Clifford Frez, Mahmood Bagheri, Ryan M. Briggs, and Siamak Forouhar**
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