Temperature-dependent Optical Gain and Loss in Continuous-wave Quantum Cascade Lasers between 8.2-10.3 μm

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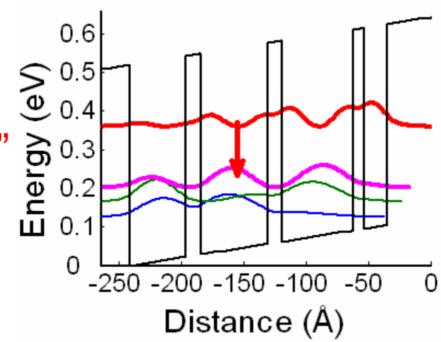
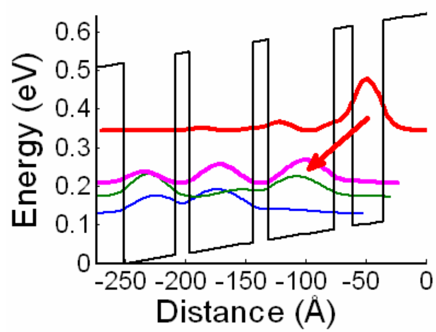
Motivation

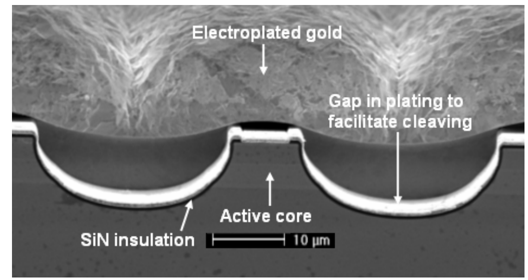
- Understand QC laser performance
- Improve laser designs
- Limited high-quality gain and loss data

“Vertical transtion”

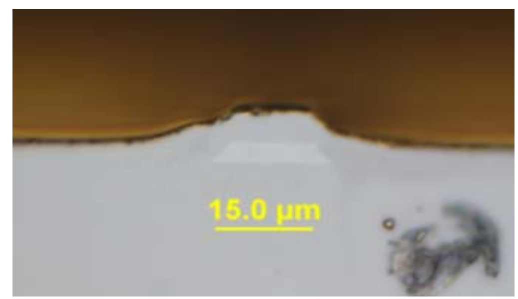


“Diagonal transtion”





Ridge waveguide

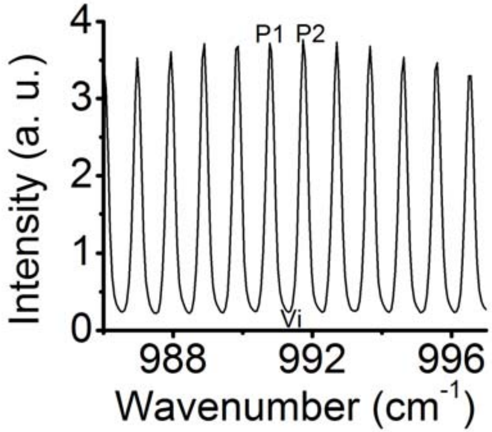


Buried heterostructure

Measurement methods

- 1/L method $$J_{th} = \frac{\alpha_W + \alpha_M}{g\Gamma} = \frac{\alpha_W}{g\Gamma} - \frac{\ln(R)}{g\Gamma}\frac{1}{L}$$
  - Need several reliable devices
  - Sensitive to threshold measurements especially at low temperature
- Hakki-Paoli method $$g\Gamma J - \alpha_W = -\frac{1}{L}\left(\ln\left(\frac{V^{1/2}+1}{V^{1/2}-1}\right) - \ln\left(\frac{1}{R}\right)\right) = y \qquad V = \frac{P_1 + P_2}{2V_i}$$
  - Need only one reliable device (short cavity, narrow laser ridge, “clean” spectrum)
  - Preferred in this study

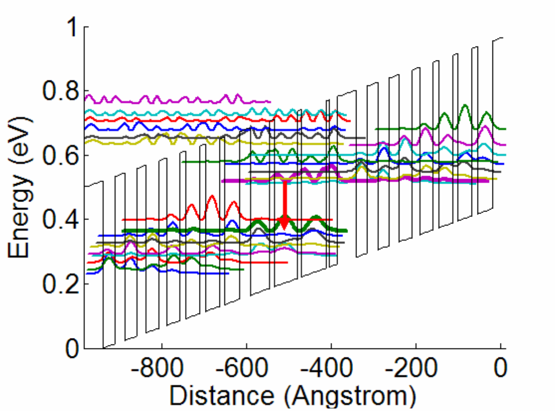
B. W. Hakki, et al., J. Appl. Phys. **46**, 1299–1306 (1975)

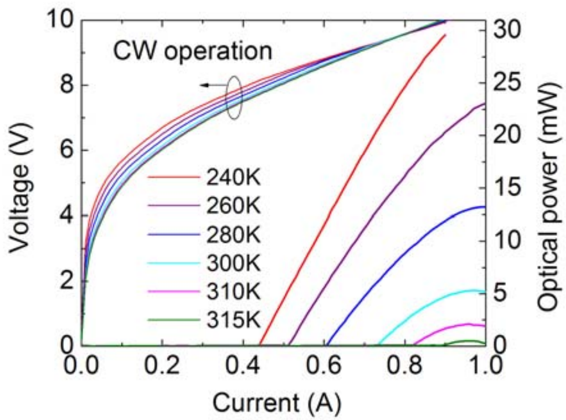


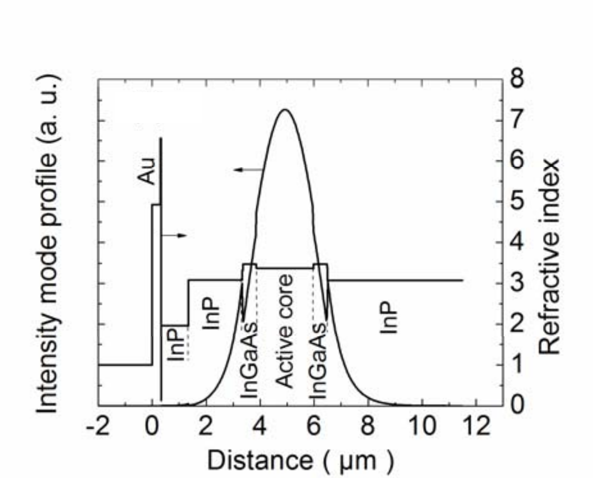
- Transmission technique and others

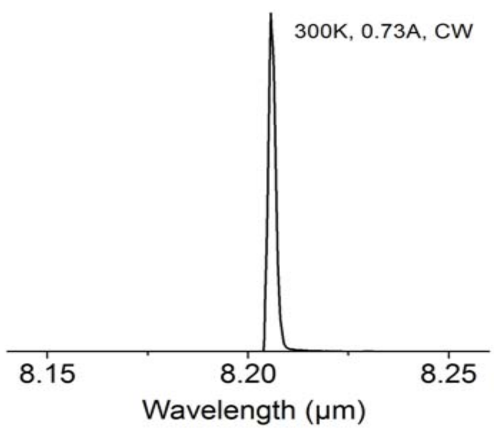
D. G. Revin, et al., J. Appl. Phys. **95**, 7584-7587 (2004)

Design and performance of “vertical transition” QC lasers (QCV1) at λ~8.2 μm

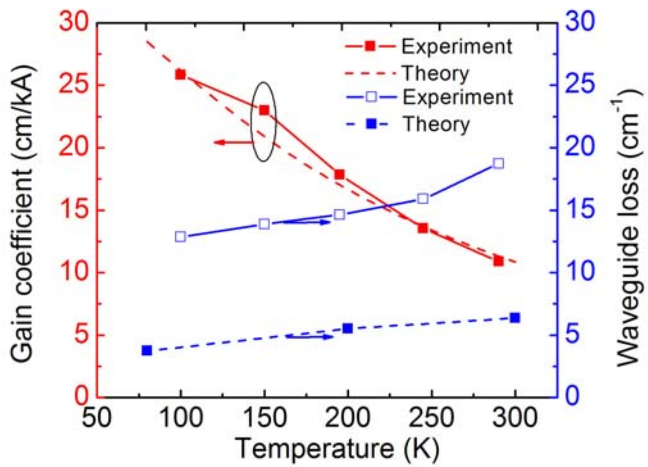






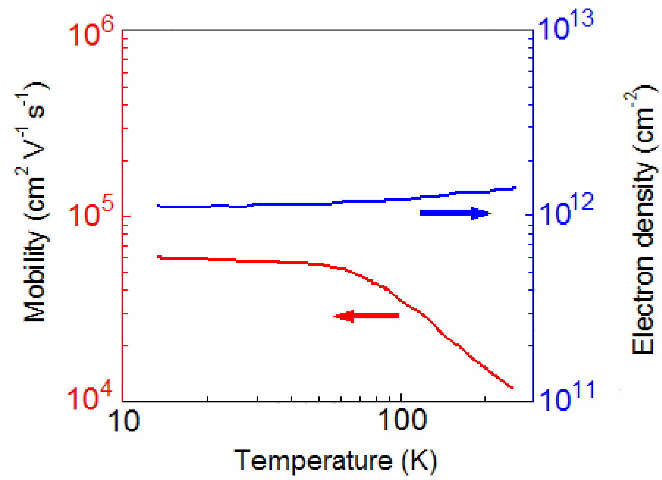


Gain and loss of "vertical transition" QC lasers (QCV1) at λ~8.2 μm



$$\varepsilon = \varepsilon_\infty - \omega_p^2/(\omega^2 + i\,\omega/(2\pi c\tau))$$

M. A. Ordal, et al., Appl. Opt. **22**, 1099-1119 (1983)

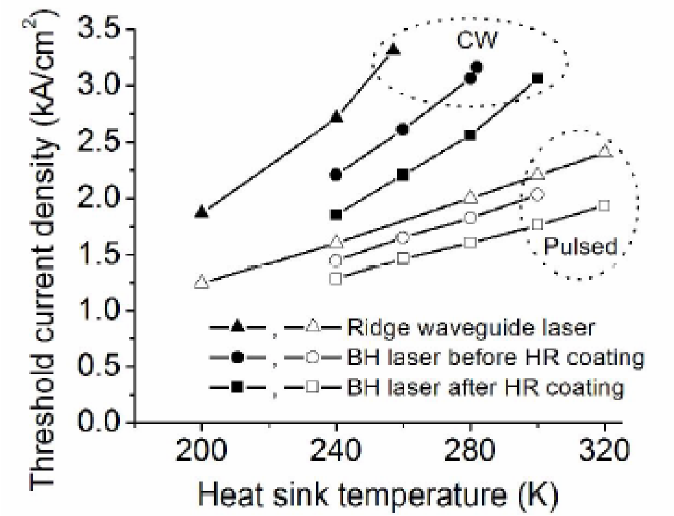


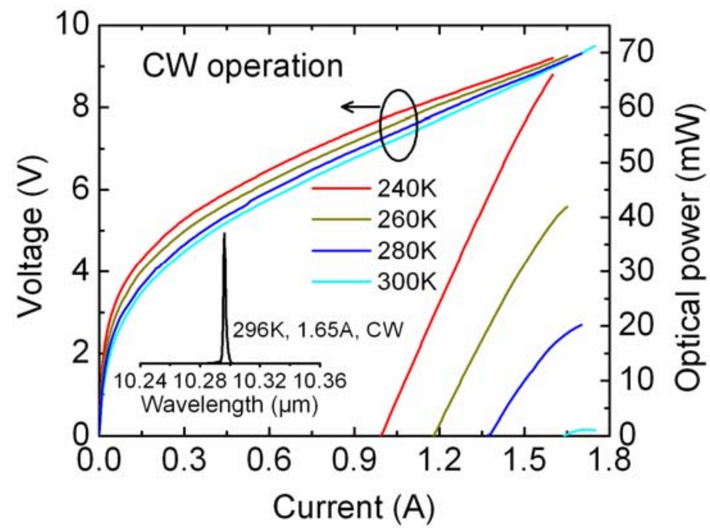
after T. Matsuoka, et al., *Jpn. J. Appl. Phys.* **29,** 2017 (1990).

► Measured gain agrees well with the design

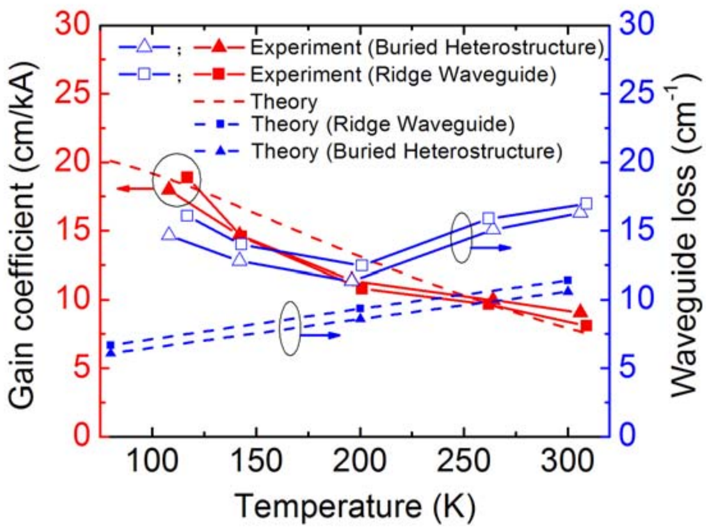
► Measured waveguide loss is much higher than calculated free carrier absorption

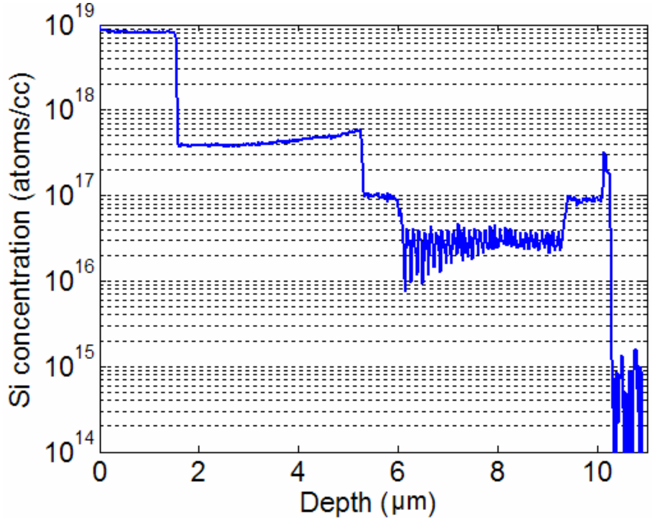
Performance of "vertical transition" QC lasers (QCV3) at λ~10.3 μm





Gain and loss of “vertical transition” QC lasers (QCV3) at λ~10.3 μm (Ridge waveguide Vs. BH)

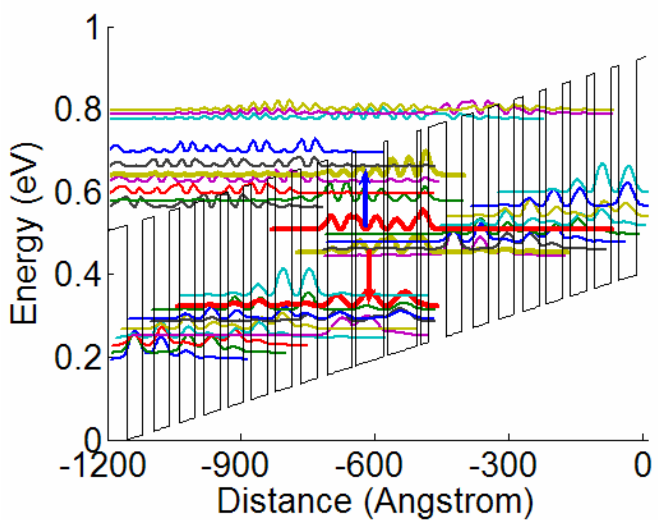


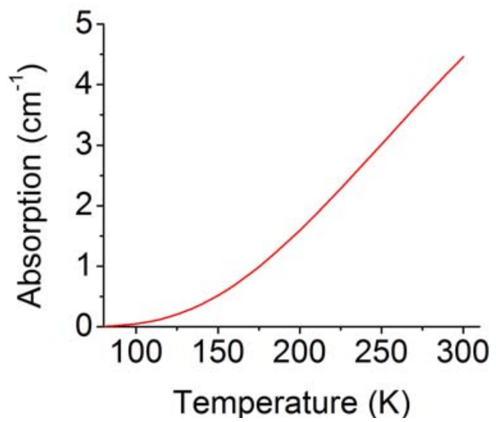


► Measured waveguide loss is higher than calculated free carrier absorption

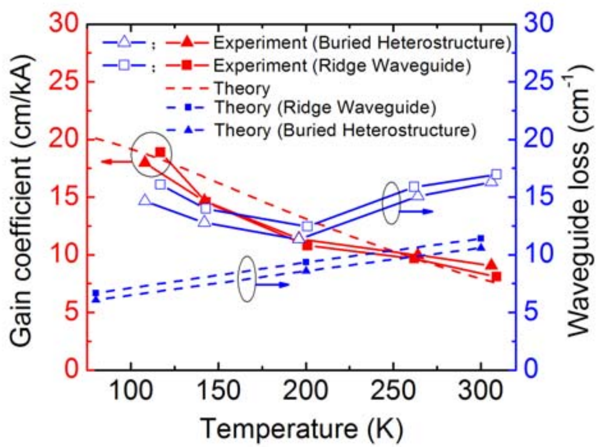
► Side-wall SiN/Au is not the major loss origin

Intersubband resonant absorption

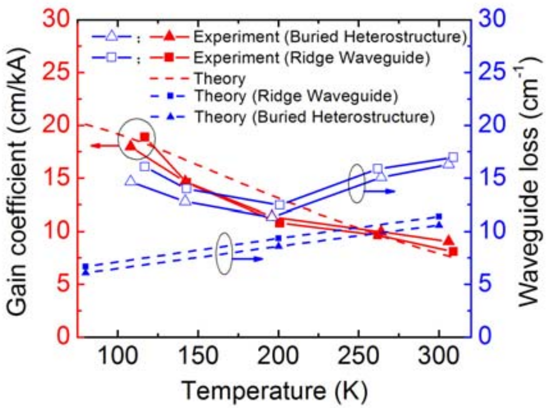




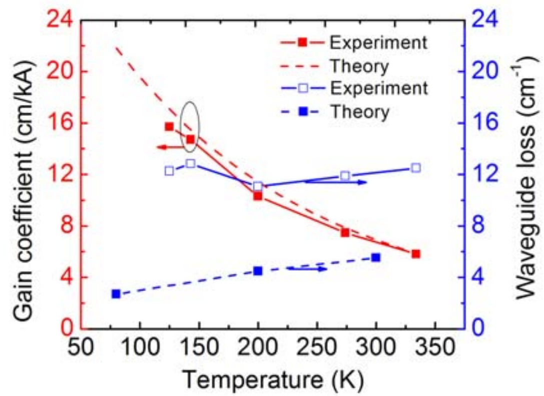
- ► Resonant absorption accounts for the difference at room temperature
- ► Large discrepancy remains in low temperature range



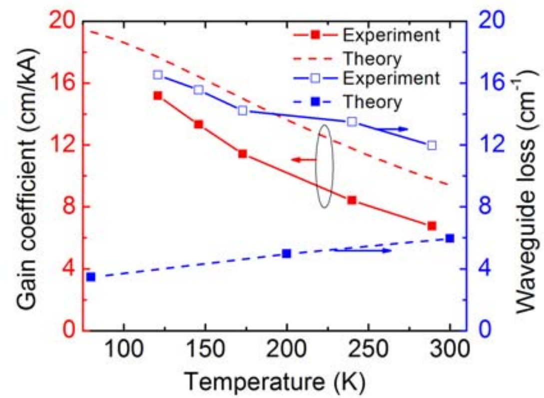
Same waveguide with different active region designs



10.3µm, vertical transition (QCV3)



9.6µm, vertical transition (QCV2)



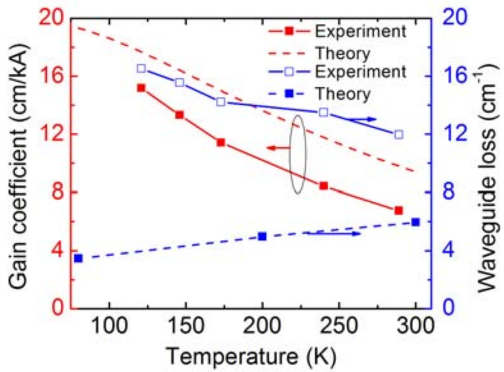
9.8µm, diagonal transition (QCD1)

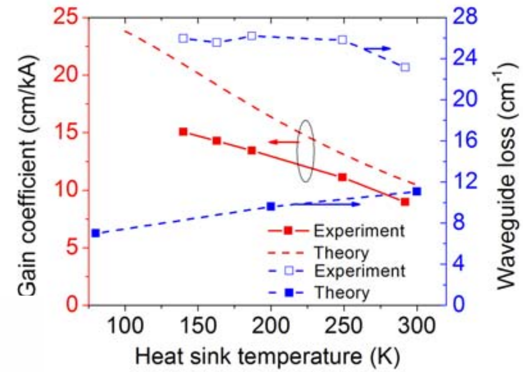
► Gain agrees well with design for vertical transition lasers, and but is smaller than modeling for diagonal transition laser.

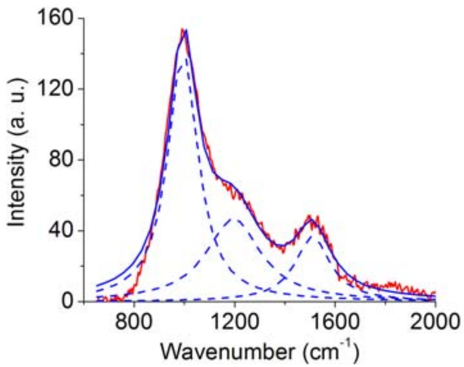
► Higher waveguide loss than calculated free carrier absorption

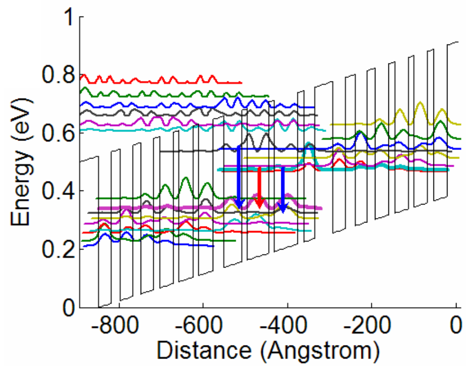
► Complex temperature-dependence of waveguide loss

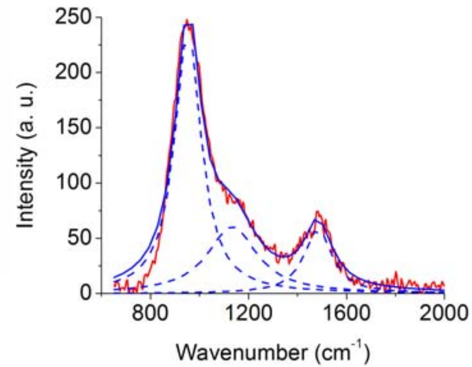
Gain and loss for “diagonal transition” QC lasers at λ~9.8 (QCD1) and 10.1 (QCD2) μm





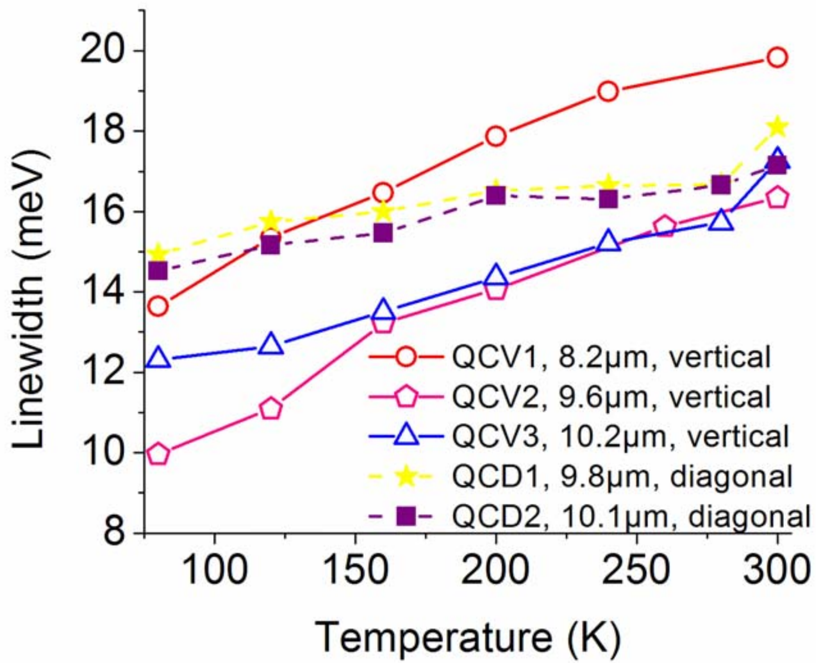






- ► Parasitic optical transitions result in smaller gain.
- ► Much higher loss and unexpected temperature-dependence means other loss origins other than free carrier absorption (resonant absorption, scattering loss, interface state absorption, etc.)

Gain spectrum line-width measurements



- ► Longer wavelength lasers have smaller linewidth
- ► Diagonal transition lasers have larger, but less temperature-sensitive linewidth

Summary

- **Gain coefficient**
  - ♦ Agrees well with modeling for vertical transition lasers
  - ♦ Smaller than the design for diagonal transition lasers partially due to parasitic carrier leakage

- **Waveguide loss**
  - ♦ Within range of 12-25cm^{-1}, much higher than free carrier absorption calculation (3-12cm^{-1})
  - ♦ Intersubband resonant absorption has shown to be an important factor
  - ♦ Complicated temperature-dependence (constant, increasing or decreasing) indicates unidentified loss origins in the active core (accidental resonant absorption, interface/defect states, etc.)

- **Acknowledgments**

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