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# 2.25- $\mu\text{m}$ optically-pumped semiconductor disk laser using multiple gain elements

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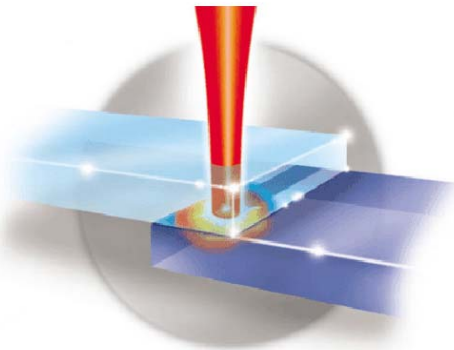


# Outline

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- Scaling-limits of single-chip OPSDLs
- Dual-chip OPSDL
- Round trip losses and threshold analysis
- Summary

# Applications for High-Brightness 2.X- $\mu\text{m}$ Semiconductor Lasers



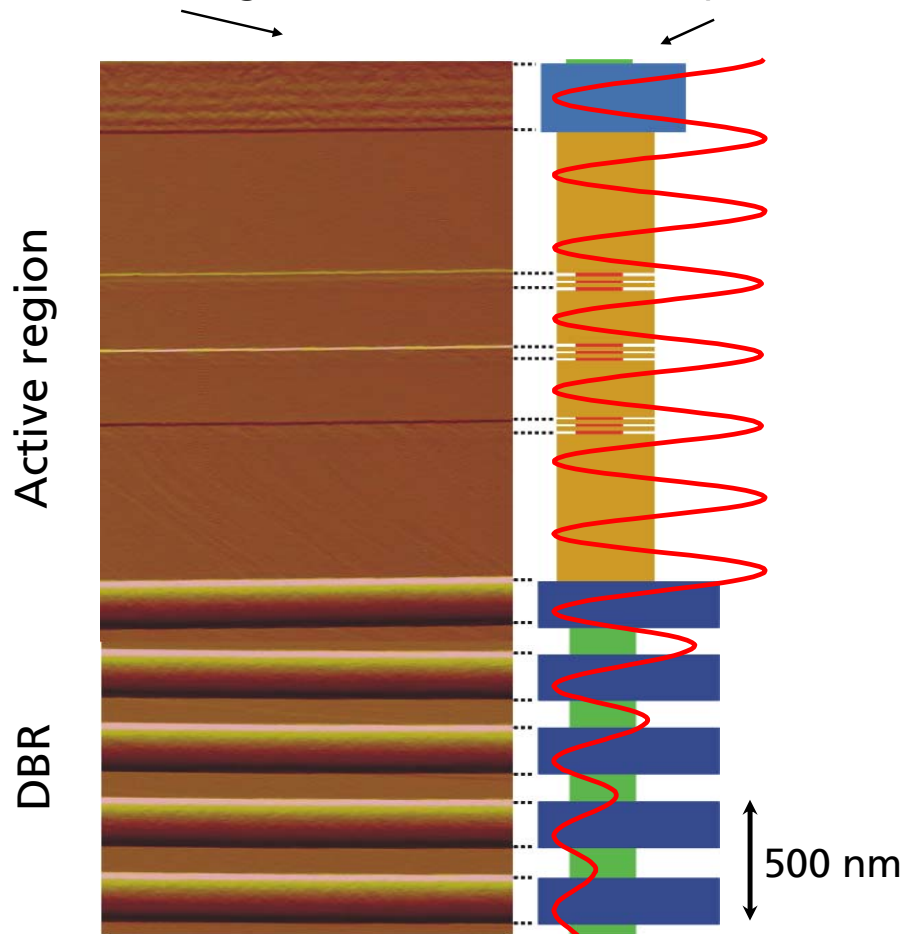
- High-resolution gas spectroscopy
  - Process control
  - Environmental monitoring
  - Remote sensing
- Optical free-space communications
- Laser surgery
- Materials processing
- Optical pumping and seeding
- Infrared countermeasures (IRCM & DIRCM)



# 2.25- $\mu\text{m}$ GaSb-based OPSDL: Epitaxial Structure

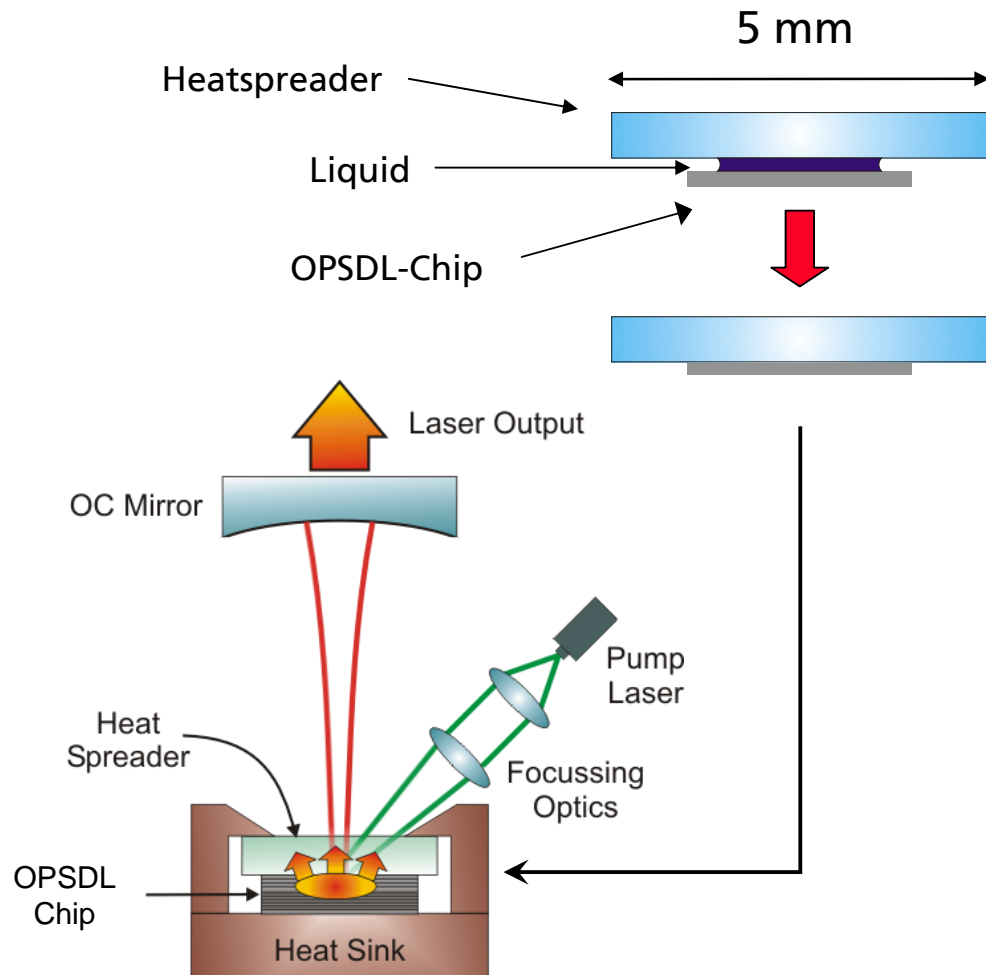
OPSDL chip (crosssectional view, AFM Image)

Band edge profile + standing wave pattern



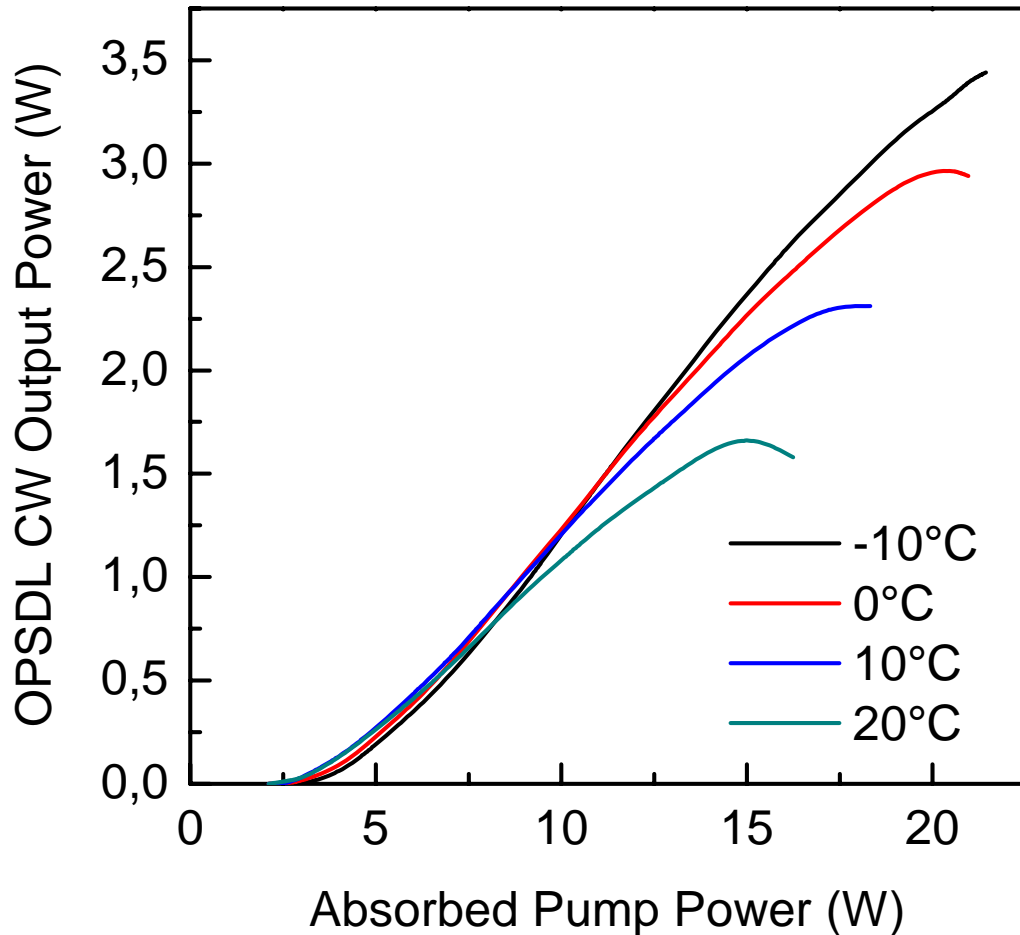
- MBE growth on GaSb-substrates
- Total epi-layer thickness: 10  $\mu\text{m}$
- Distributed Bragg-reflector (DBR): 21  $\frac{1}{2}$  GaSb / AlAsSb layer pairs
- Active region (thickness: 3  $\mu\text{m}$ ):
  - $\text{Al}_{0.30}\text{Ga}_{0.70}\text{As}_{0.024}\text{Sb}_{0.976}$  barrier layers  
→ ~90 % pump absorption
  - 10  $\text{Ga}_{0.64}\text{In}_{0.36}\text{As}_{0.10}\text{Sb}_{0.90}$ -QWs
  - $\text{Al}_{0.85}\text{Ga}_{0.15}\text{As}_{0.068}\text{Sb}_{0.932}$  window layer
  - GaSb cap layer
  - RPG active region layout

# Thermal Management: Intra-Cavity Heatspreader



- Materials: SiC or diamond
- Liquid capillary bonding
- Thickness: ca. 300  $\mu\text{m}$
- Typical thermal resistance (SiC, pump spot diameter:  $\sim 400 \mu\text{m}$ ): 5 K / W

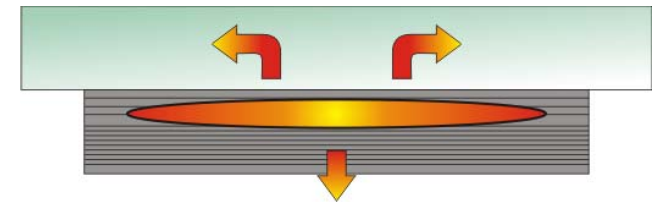
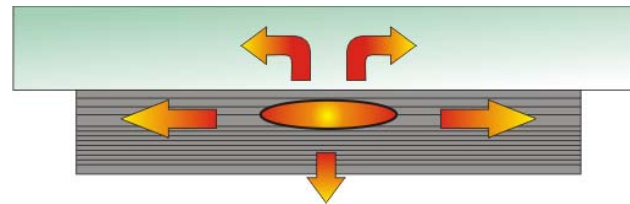
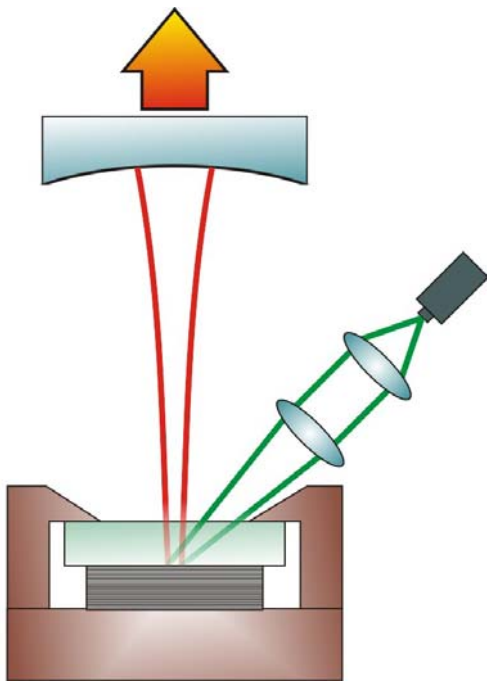
# Single-Chip OPSDL: High-Power CW Operation



- Emission wavelength: 2.25  $\mu\text{m}$
- Pump source: diode laser (980 nm)
- CW output power with SiC heatspreader: > 3.4 W @ -10°C (1.6 W @ +20°C)
- Slope efficiency: 24 % @ -10°C  
→ Diff. quantum efficiency: 55% @ -10°C

# Limits of Power Scaling using Single-Chip OPSDLs

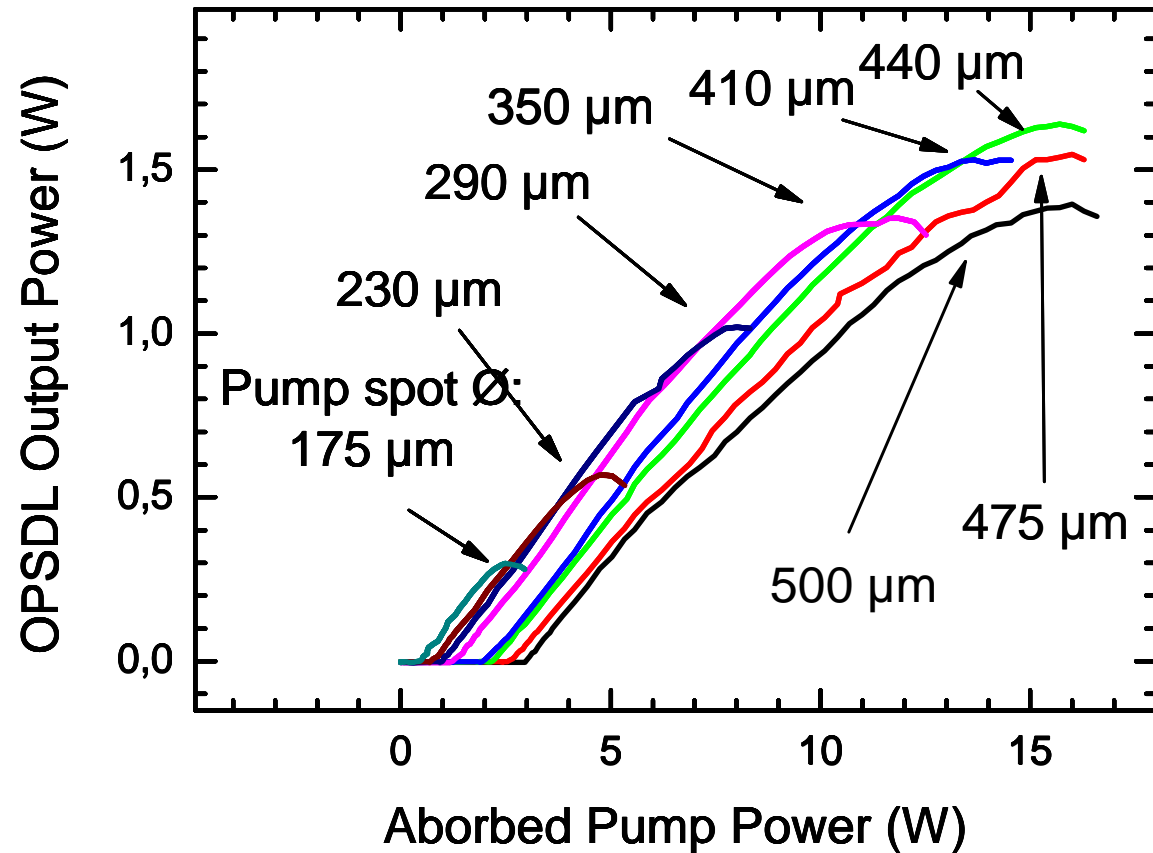
- Single-chip power scaling scheme: increase of pumped area at constant pump power density
- Maximum output power limited
  - Thermal resistance not  $\propto 1/\text{pumped area}$ :
    - 3D heat transfer
    - Impeded radial heat flow at large pump spot size



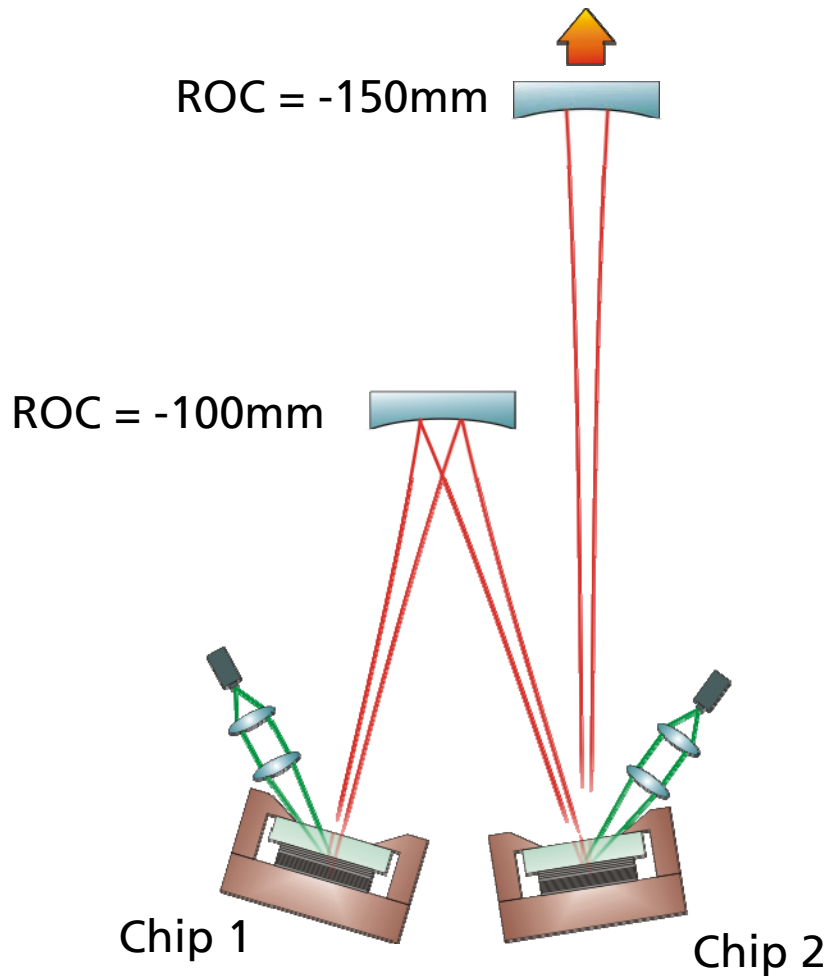
# Power scaling in single-chip OPSDLs

2.25- $\mu\text{m}$  OPSDL, SiC heat spreader,  $T=20^\circ\text{C}$

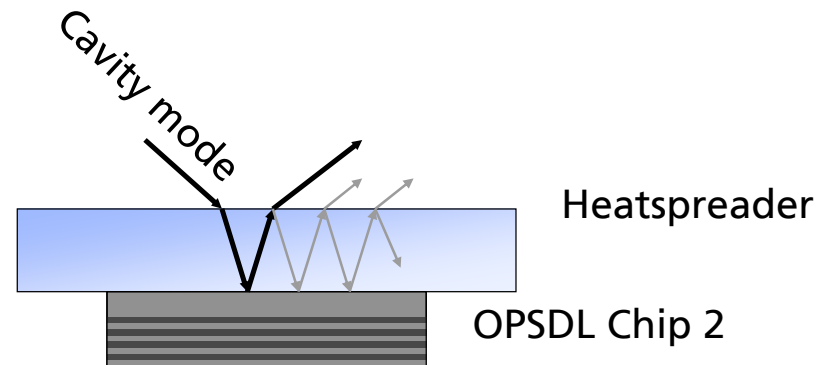
- No unlimited increase in maximum output power when the pump spot diameter is increased



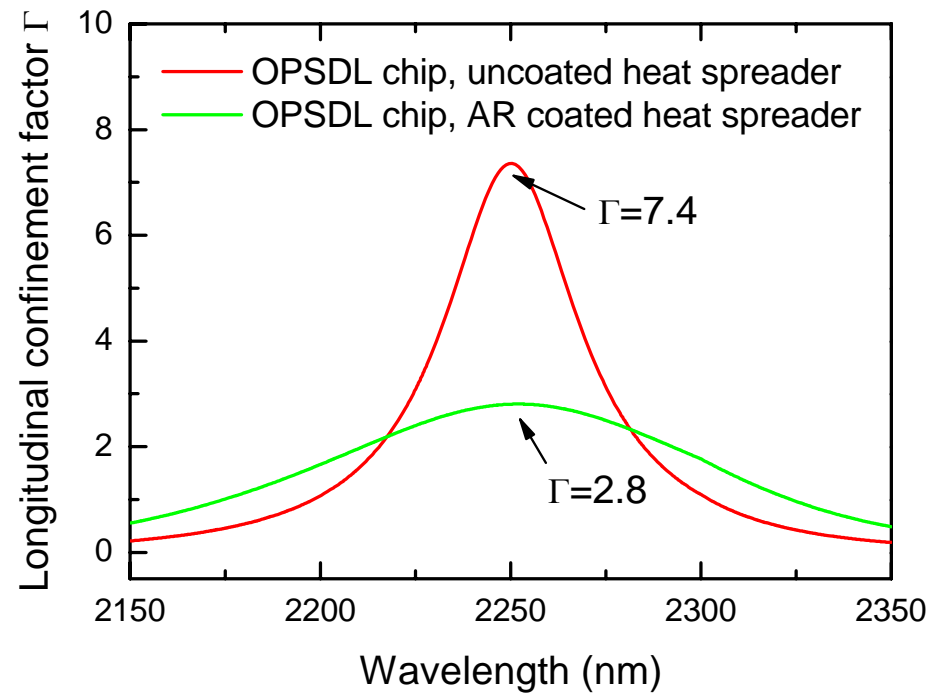
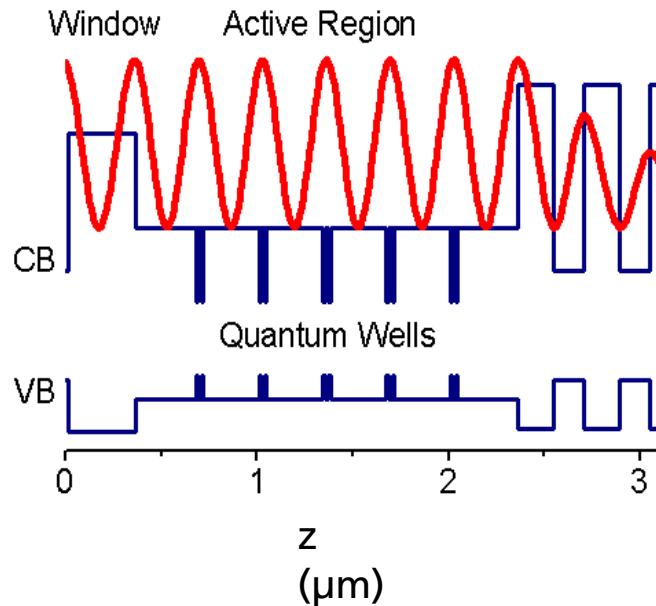
# Dual-Chip Configuration



- Power scaling scheme: coupling of several chips
- Delayed thermal rollover compared to single-chip OPSDL
- Folded cavity:  
Chip 1 = end mirror, chip 2 = folding mirror
- Use of chip 2 as folding mirror requires AR coating to prevent walk-off losses

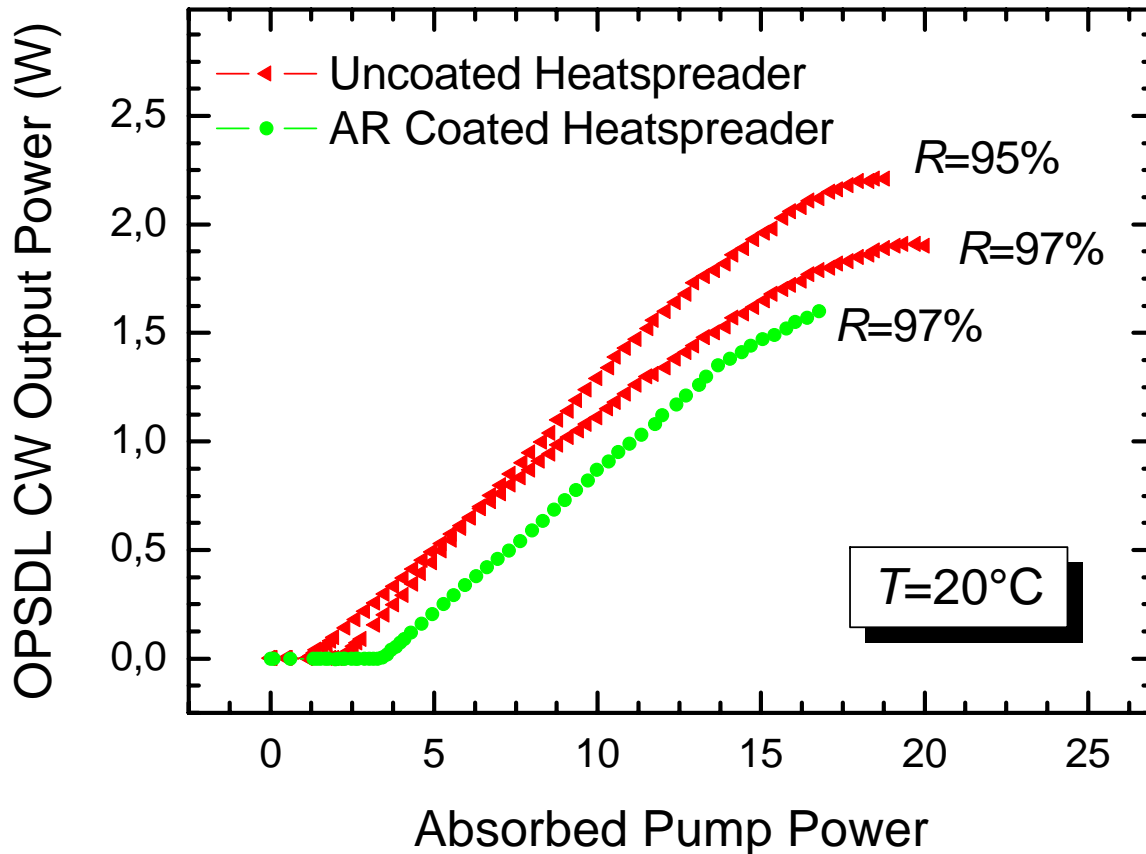


# Longitudinal Confinement Factor



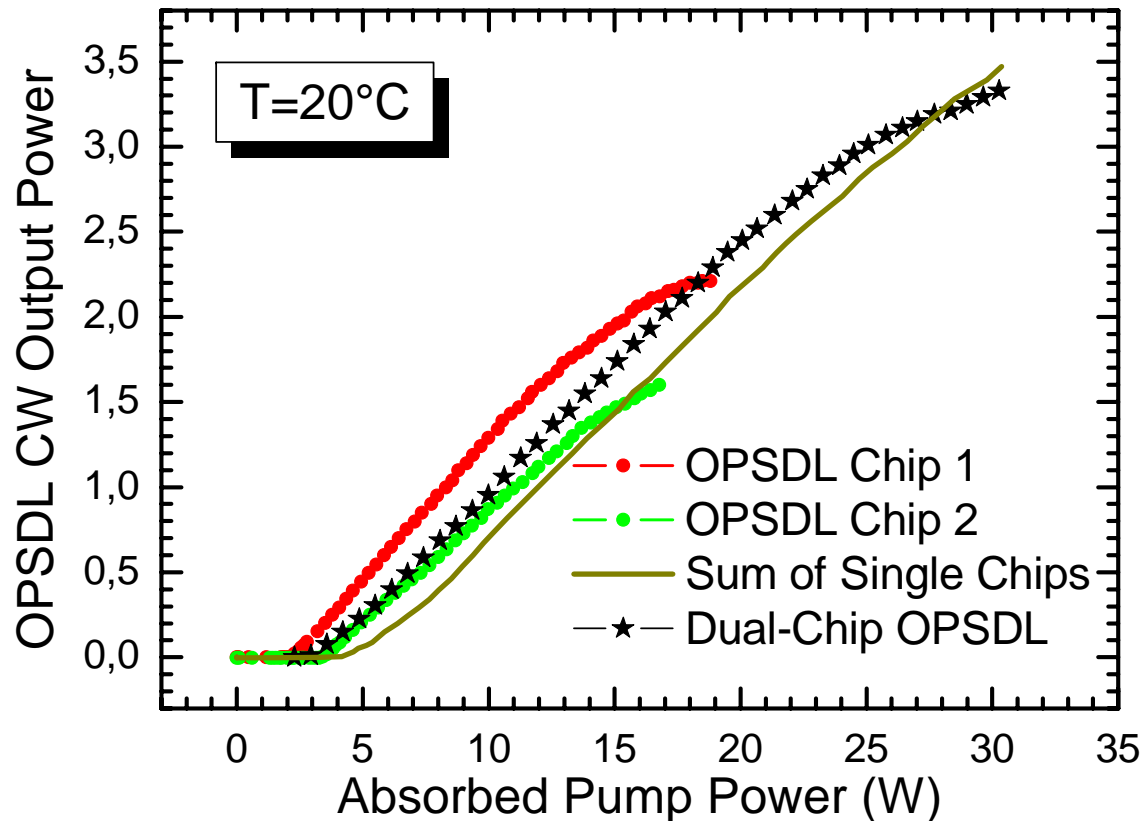
- OPSDLs with uncoated heat spreaders: gain enhancement by microcavity resonance
- OPSDLs with AR coated heat spreader: microcavity resonance strongly reduced (factor 2.6)

# Chip characterization in a single-chip cavity



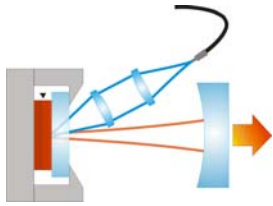
- Linear cavity
- Comparison: chips bonded to AR coated ( $2.25\mu\text{m}$ ) / uncoated heatspreaders
  - Higher threshold pump power with AR coated heatspreader
  - Uncoated heatspreader allows for lower output coupler reflectivities
  - AR coated:  $>1.6\text{ W @ }20^\circ\text{C}$   
uncoated:  $>2.2\text{ W @ }20^\circ\text{C}$

# Dual-Chip configuration: CW Operation

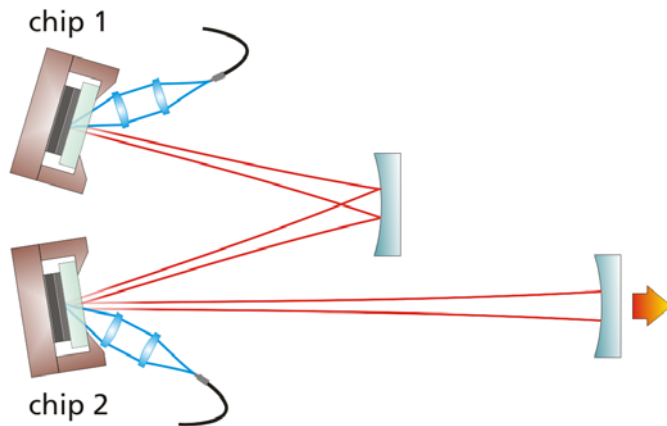


- Delayed thermal rollover
- Output coupler reflectivity: 92%
- CW power: 3.3W@20°C, (15% slope efficiency)
- Threshold pump power comparable to single-chip OPSDL

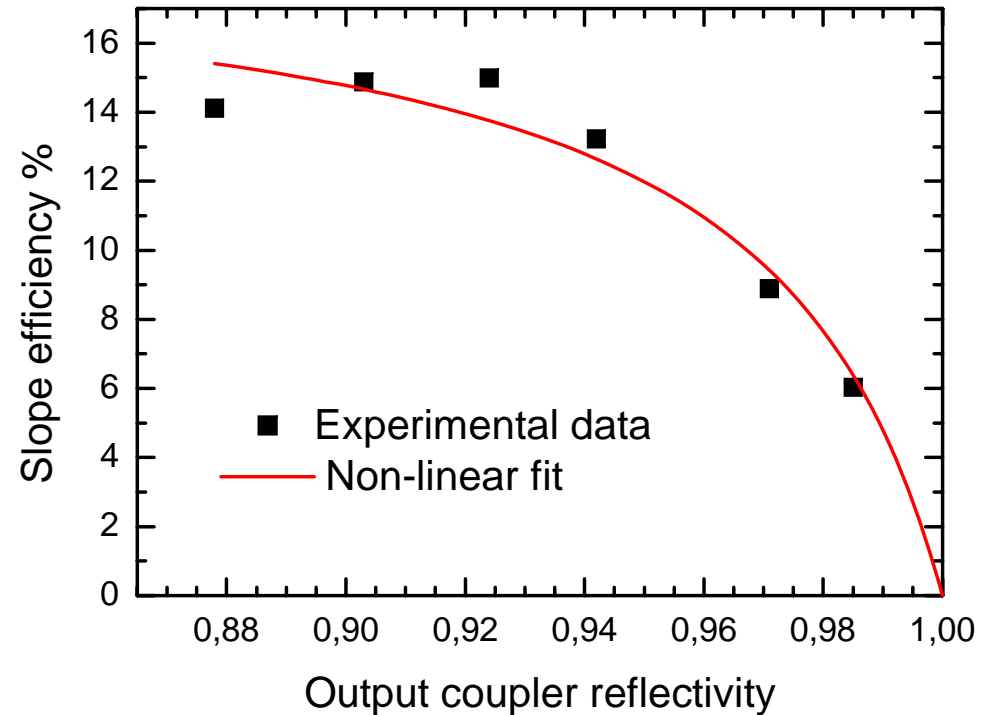
# Determination of round-trip losses



Round trip loss:  $\approx 1.2\%$

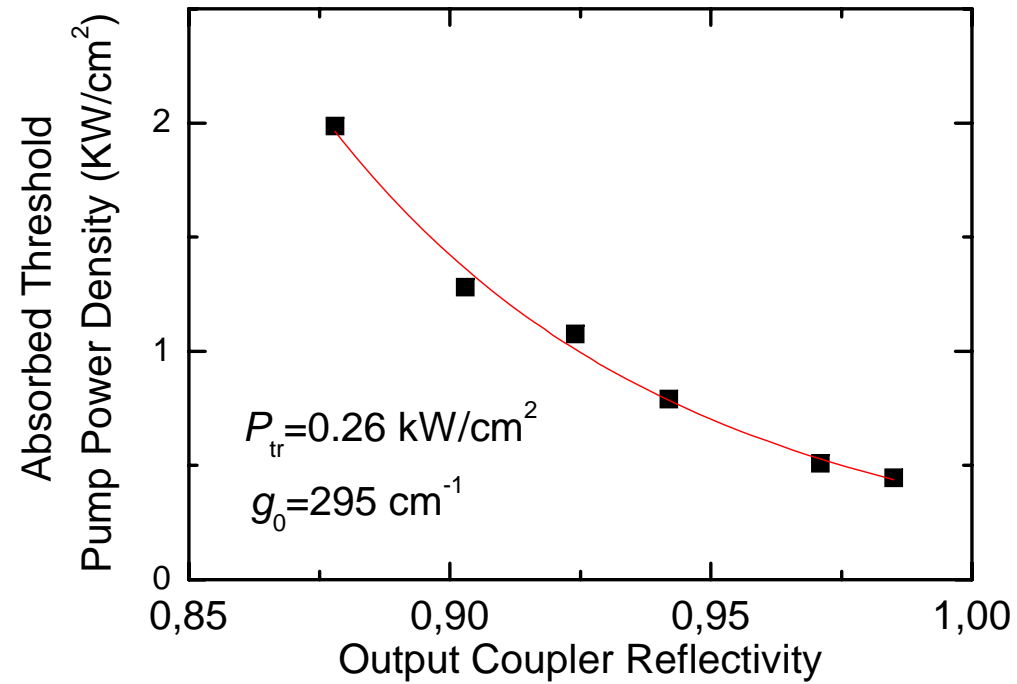
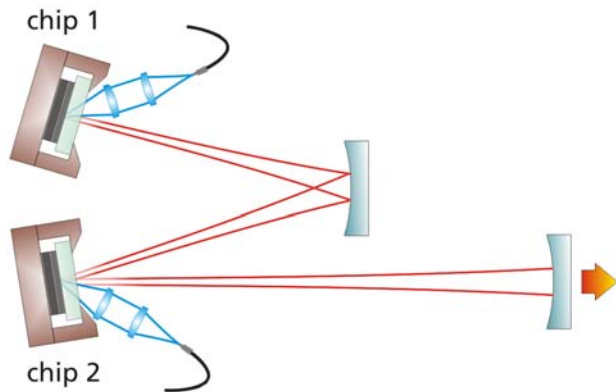


Round trip loss:  $\approx 2.5\%$



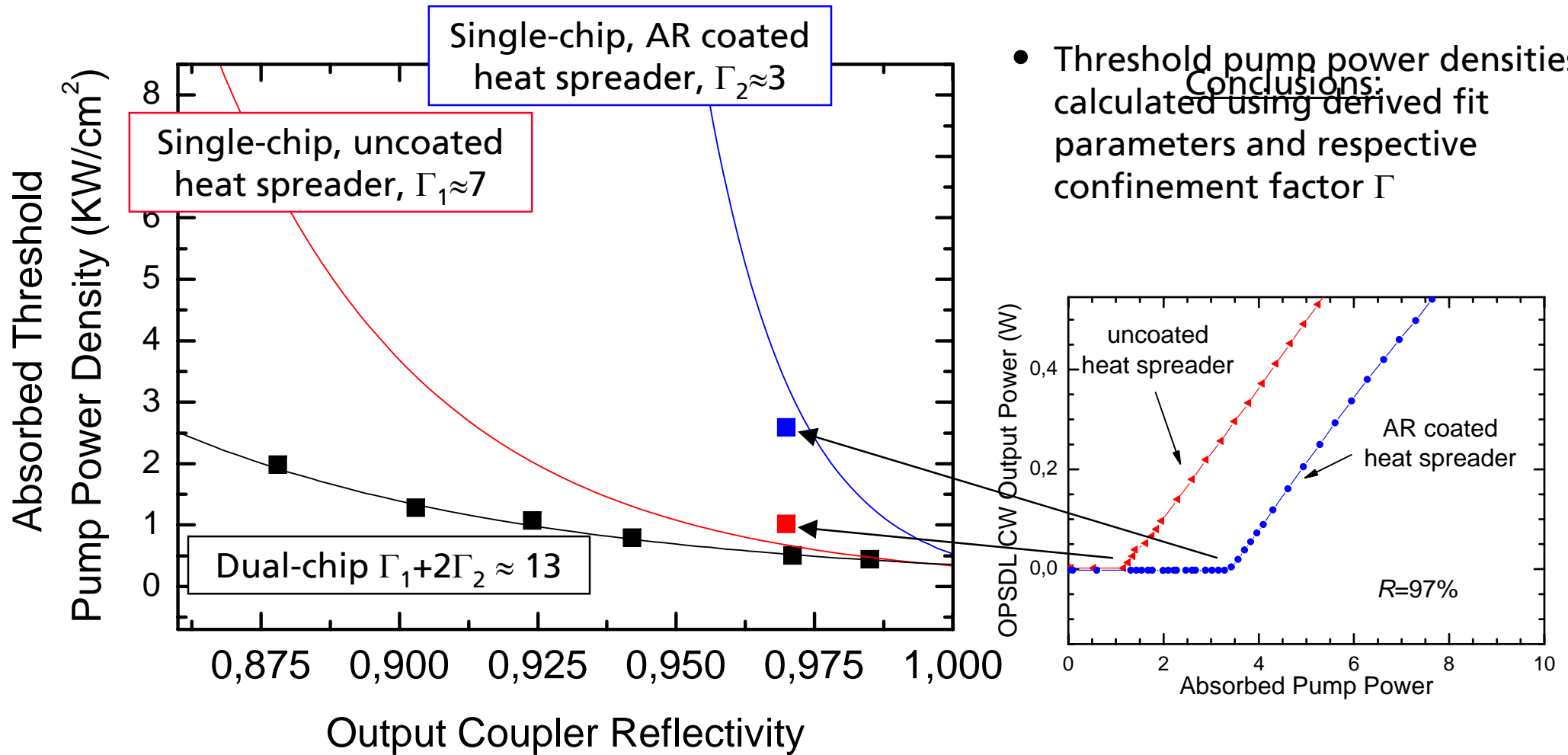
→ Increase in loss due to doubled number of gain elements

# Dual-chip OPSDL: threshold analysis



- Phenomenological laser model (logarithmic gain model) allows extraction of transparency pump power  $P_{tr}$  and gain parameter  $g_0$

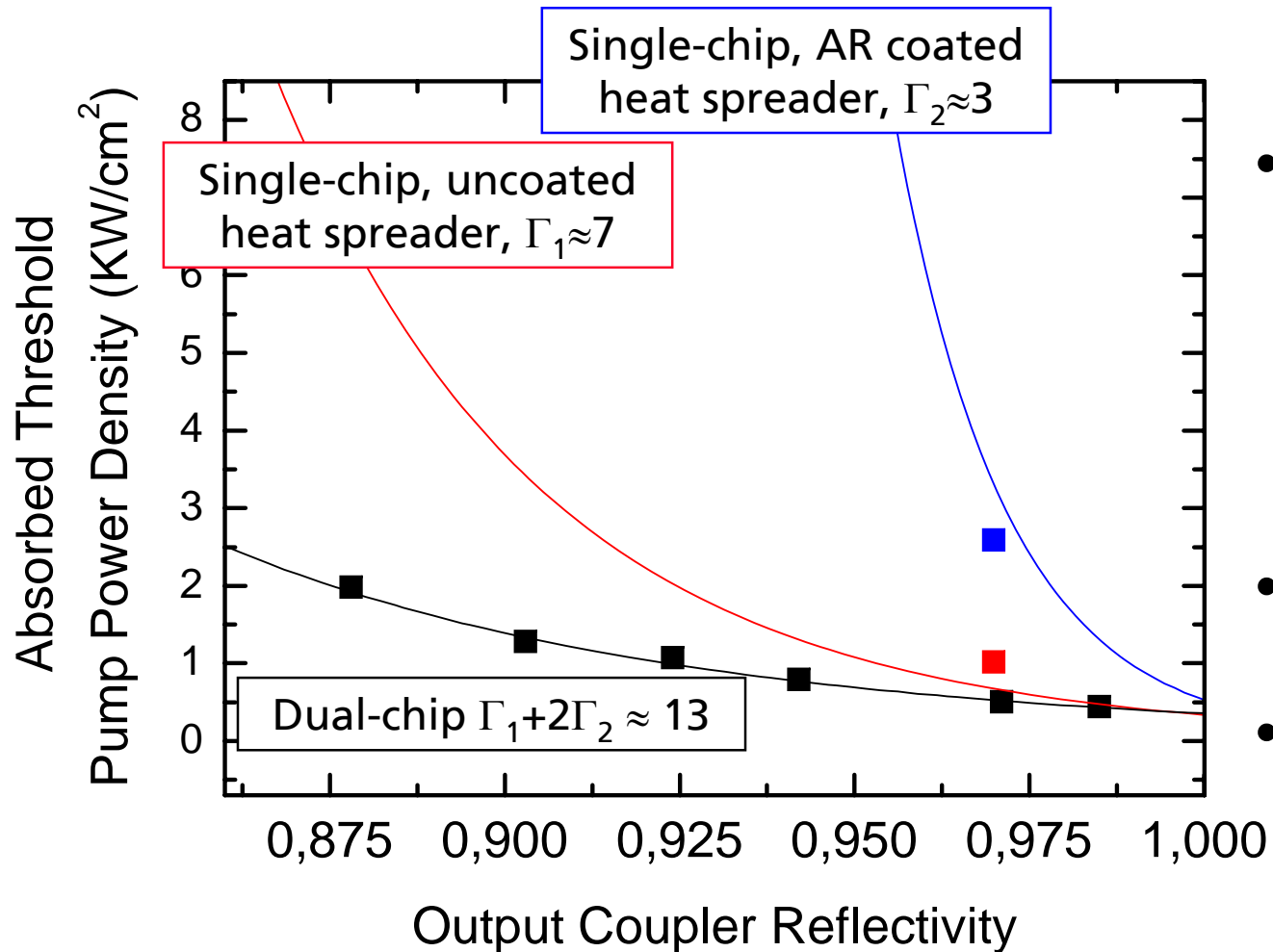
# Dual-chip vs. Single-chip OPSDL: threshold calculations



- Threshold pump power densities calculated using derived fit parameters and respective confinement factor  $\Gamma$

Conclusions:

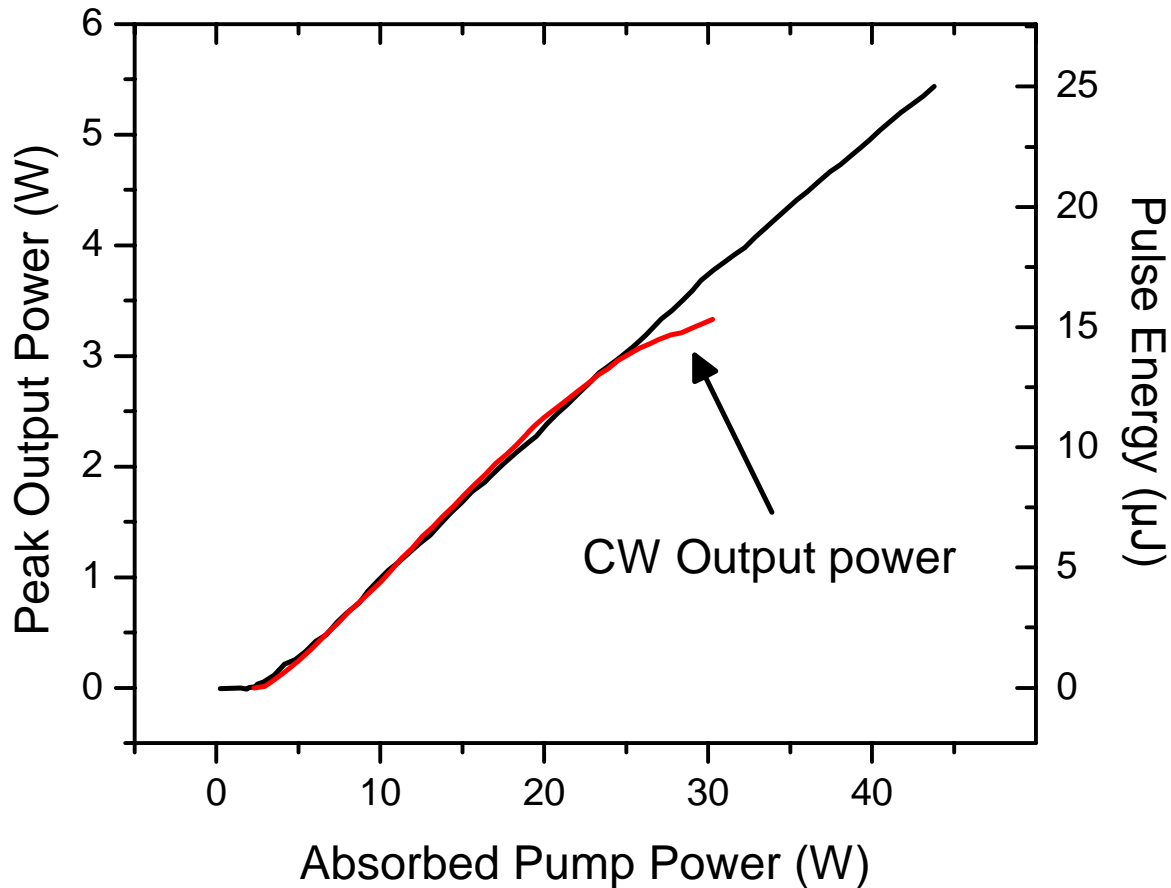
# Dual-chip vs. Single-chip OPSDL: threshold calculations



## Conclusions:

- Modal gain strongly enhanced in dual-chip operation:
  - Cavity mode traverses two gain elements
  - Cavity mode traverses chips folding the resonator four times
- Higher output coupling possible in dual-chip operation possible
- Higher output coupling can compensate increased resonator losses

# Dual-chip configuration: Pulsed operation



- Pulsed pump source: 5  $\mu\text{s}$  pulse width, repetition rate: 100 Hz
- No thermal rollover
- Pulse energies > 24  $\mu\text{J}$  (limited by available pump power)

# Summary

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- **2.25- $\mu\text{m}$  single-chip OPSDLs**
  - High-power operation demonstrated: 1.6 W-2.2 W max. CW output power @ 20°C
  - Power-scaling limited by imperfect heat removal
- **2.25- $\mu\text{m}$  Dual-chip OPSDLs**
  - Delayed thermally induced roll-over
    - 3.3W max. CW output power @ 20°C
  - Slope efficiency comparable to single-chip OPSDLs (~15%)
  - Increased modal gain
    - Compensation of increased round trip losses possible