University of Southampton

# High-power semiconductor VECSELs


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High Brightness Diode Laser Sources
Workshop at the World of Photonics Congress
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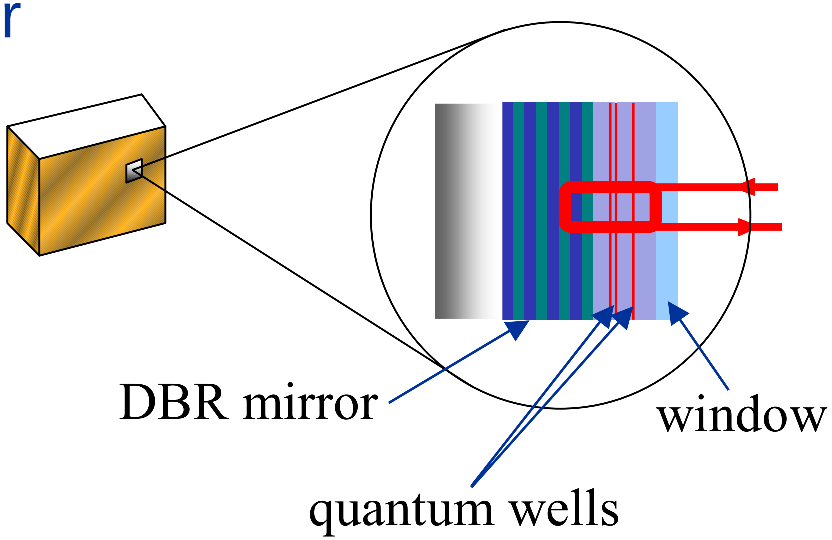
# Outline

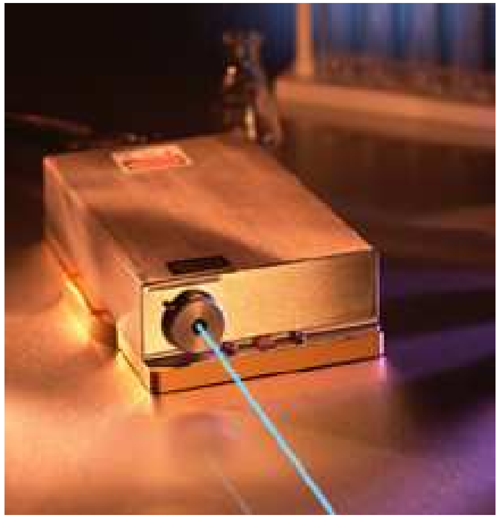
- Introduction to the ***V****ertical-****E****xternal-****C****avity* ***S****urface-****E****mitting* ***L****aser*; a power-scalable diffraction-limited semiconductor laser
  - optical pumping
  - external cavity – intracavity access for SHG
- high ***peak*** power in fs operation
- high ***cw*** power: thermal management by substrate removal, intracavity heatspreader, in-band pumping
- VECSEL-YDFA

# VECSEL characteristics

- gain element is an active mirror
- power-scalable disc laser
  - large emitting area
  - optical pumping: uniform carriers
- $TEM_{00}$ beam
  - external cavity
  - access to mode: RGB
- spectral versatility
  - quantum well laser
  - 670 nm $\rightarrow$ 2.3 µm

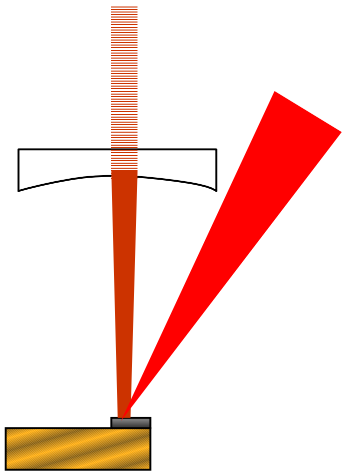


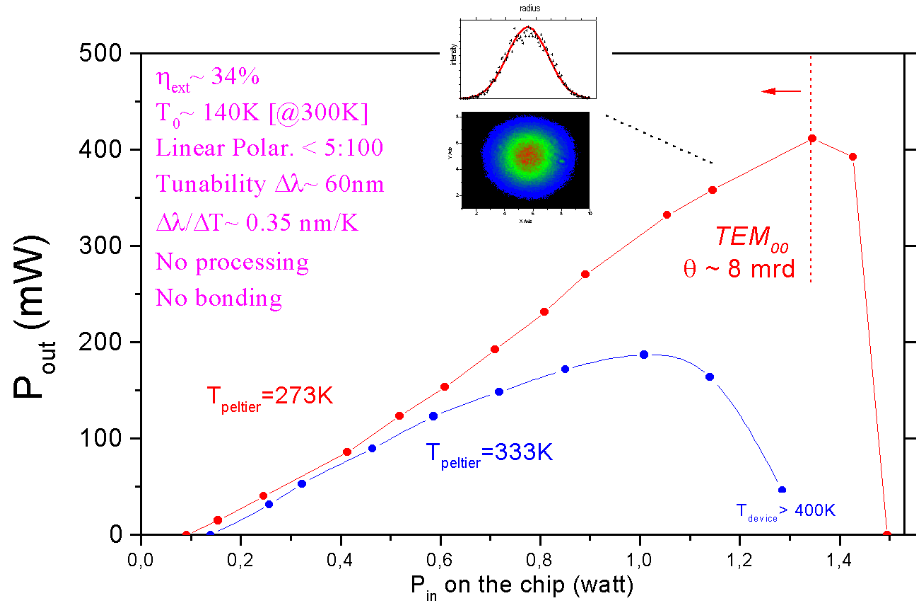

A. C. Tropper & S Hoogland
Progress in Quantum Electronics 2006



**Sapphire**
**Coherent Inc**
**200 mW at 488 nm**

# InGaAs/GaAs cw VECSEL

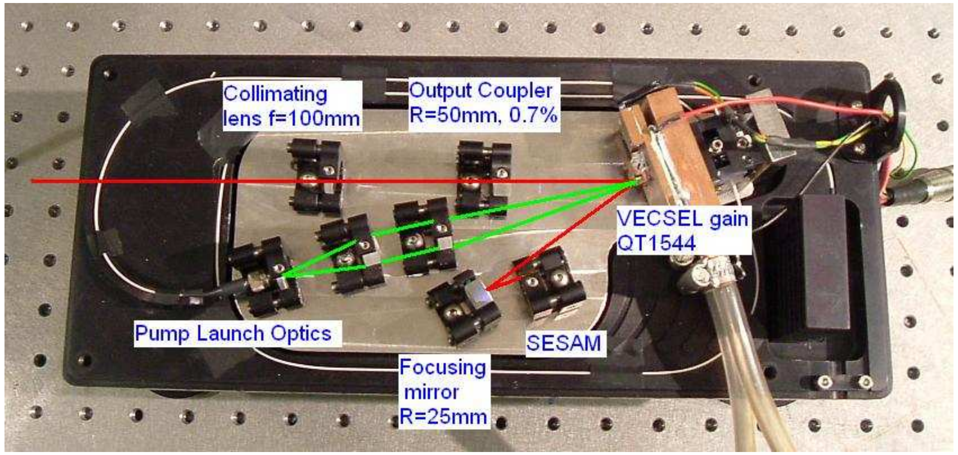


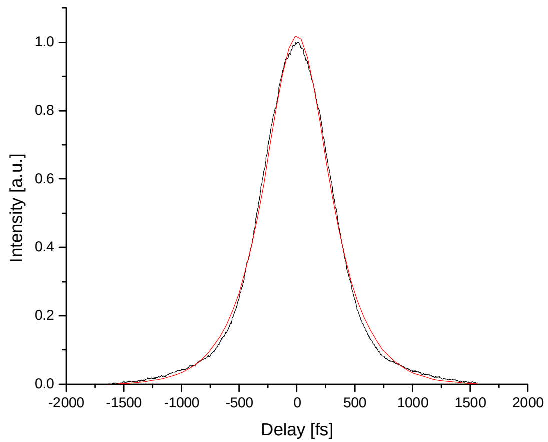



- unprocessed wafer
- 830-nm pump, 90-µm diameter spot
- 190 mW @ 60ºC
- 400 mW @ 0ºC
- 30% optical/optical efficiency

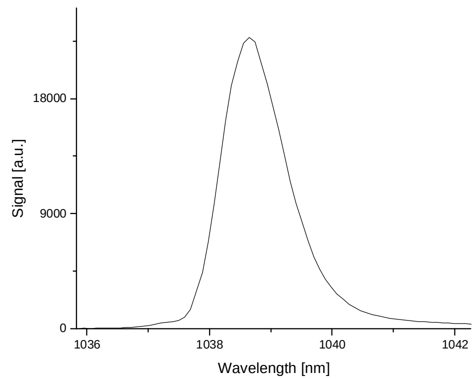
Garnache, Tropper,
J Phys D 2004

# 50 W peak power in 448-fs pulse



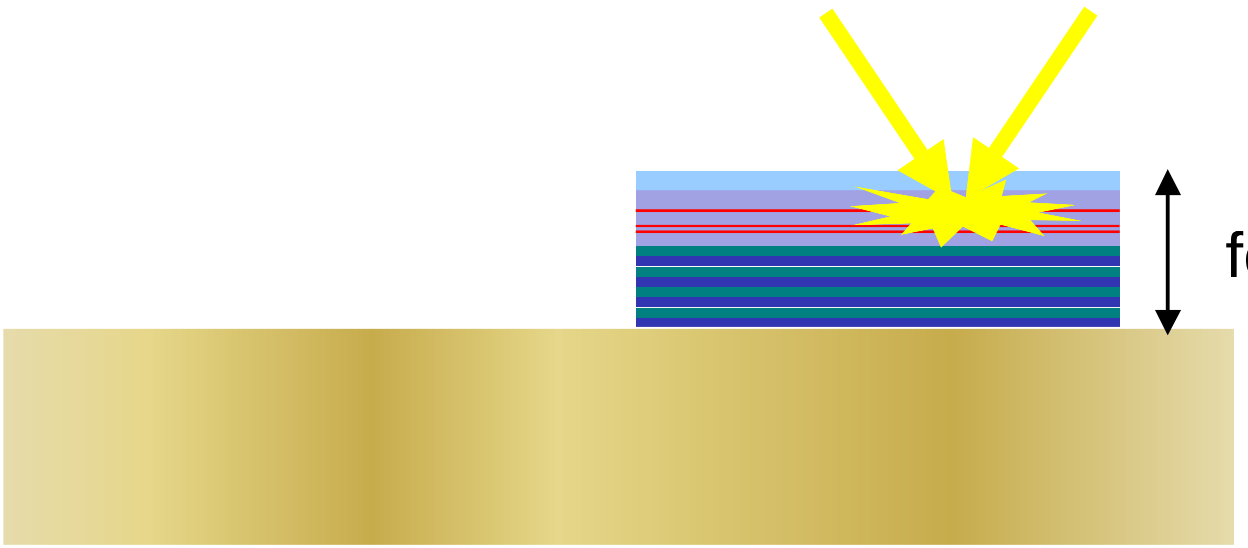




- SESAM mode-locked VECSEL
- 448-fs sech$^2$ pulse at 1038.5 nm
- 1.01× Fourier limit
- average power 40 mW @ 905 MHz
- peak power ~50 W



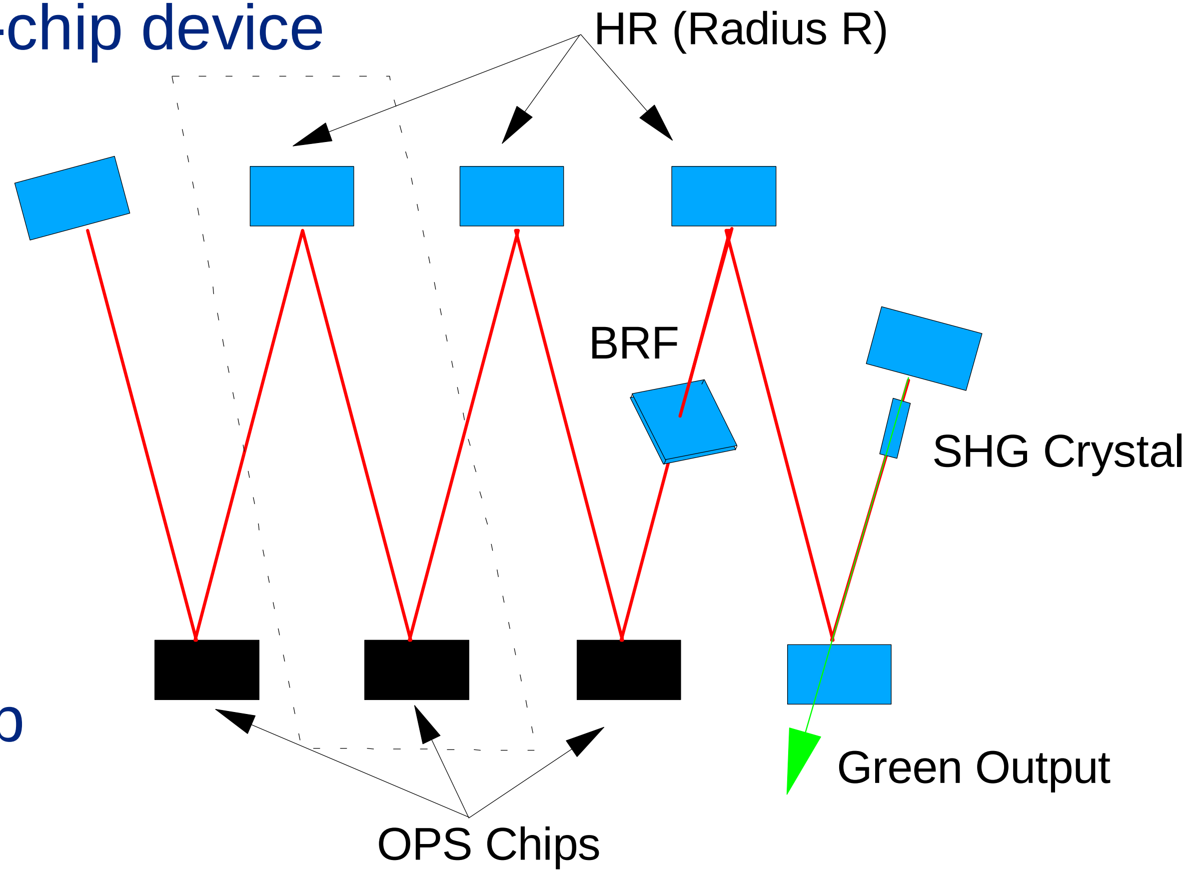
# Substrate removal

- Kuznetsov et al 1996 (Aram Mooradian’s group)
- InGaAs/GaAs QW on GaAs/AlAs DBR
- GaAs substrate removed by jet-etch
- thin, delicate structure, subject to degradation
- 920 – 1150-nm region; 460 – 570 with IC-SHG
- benchmark results from Coherent and Osram



# Multichip cavity concept

Juan Chilla: 73 W @ 980 nm from 180-W pump, 2-chip device



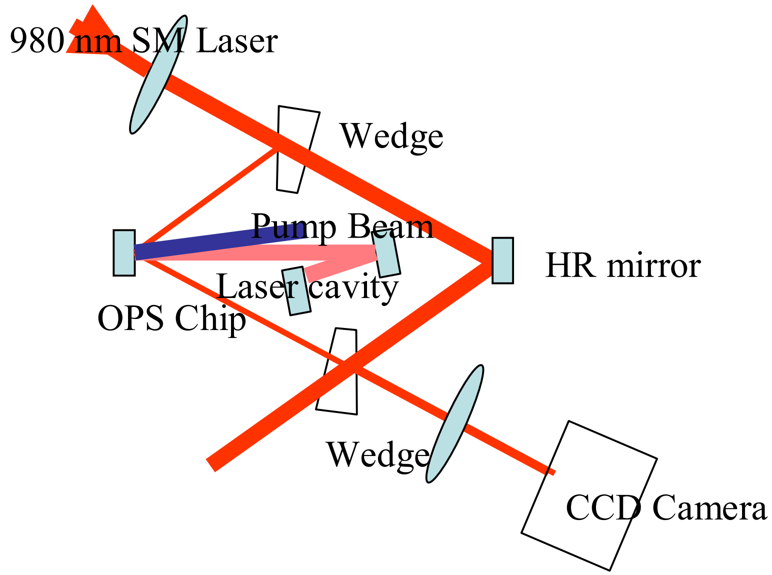

- ➔ each chip pumped independently
- ➔ modular design
- ➔ add or remove chip + folding mirror module

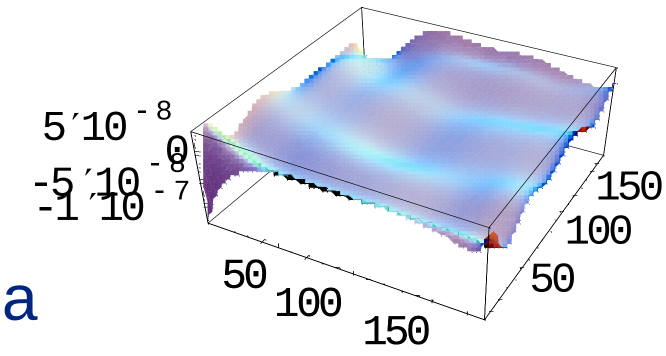
COHERENT

# Thermal lens characterization

- Mach-Zehnder, 980-nm SML
- probe pump/no pump, lasing/non-lasing

- difference pump/no pump on 980 nm OPS chip
- 70 W, 900 µm dia. spot – lens undetectable
- 9 W, 420 µm spot – barely detectable (λ/40)




Juan Chilla

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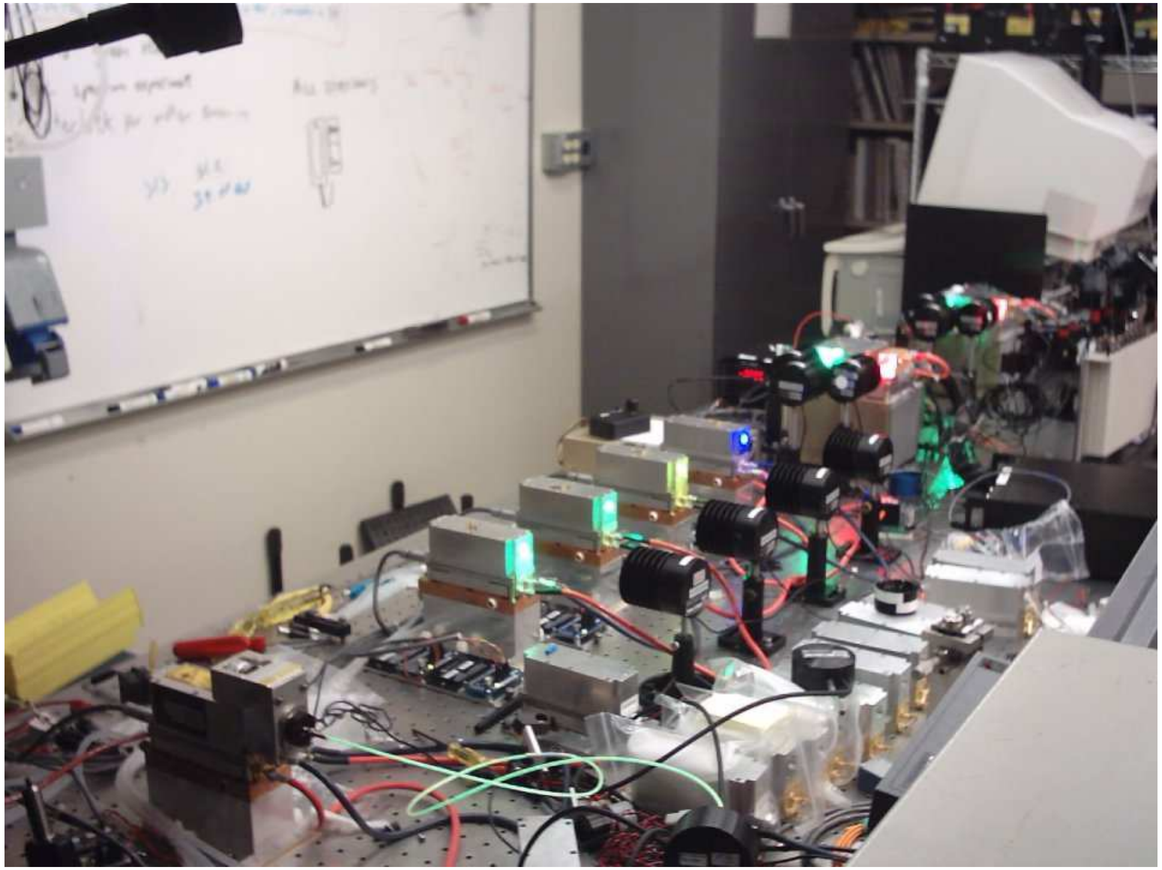
# Visible colours

- multi-watt visible wavelengths:

- blue; 460 nm
- cyan; 488 nm
- turquoise; 505 nm
- green; 532 nm
- yellow; 560 nm



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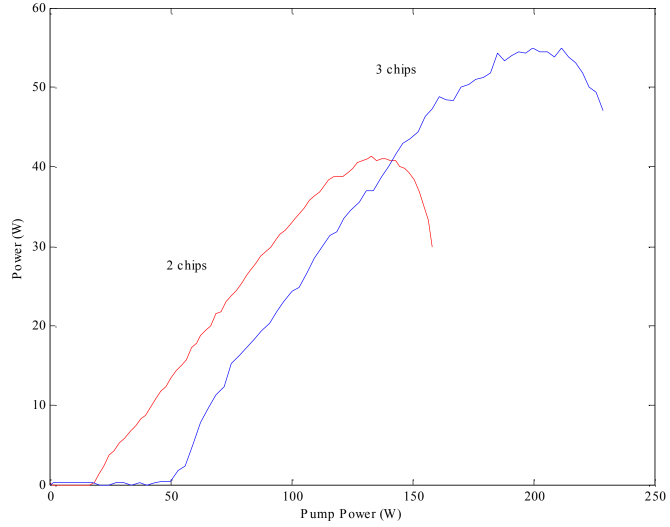
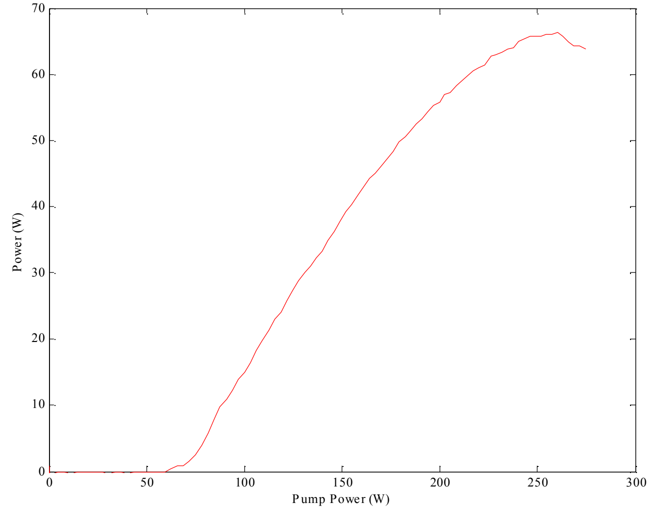
# High power 532-nm source

- pump spot diameter 900 µm
- water temperature 5ºC
- near diffraction-limited operation ($M^2$ ~ 1.3):
  - 2-chip > 40 W
  - 3-chip > 50 W




- multimode operation
  - > 60 W with ~150 W pump

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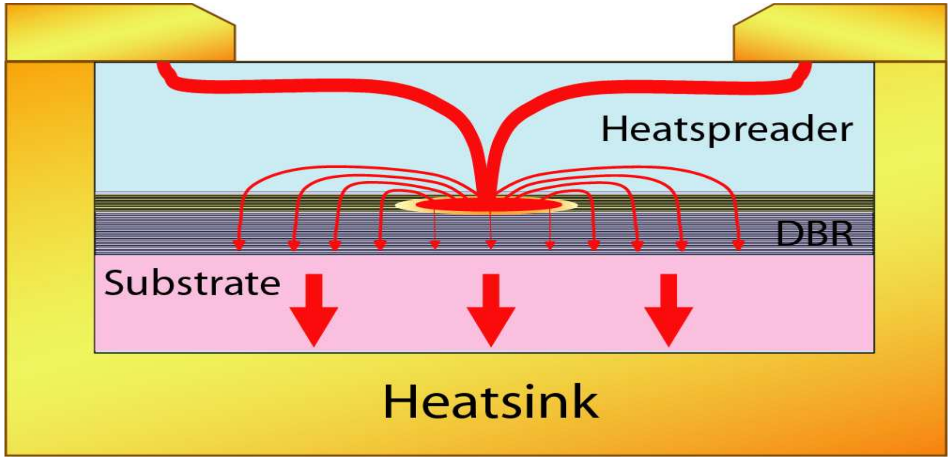
# Intracavity heatspreader



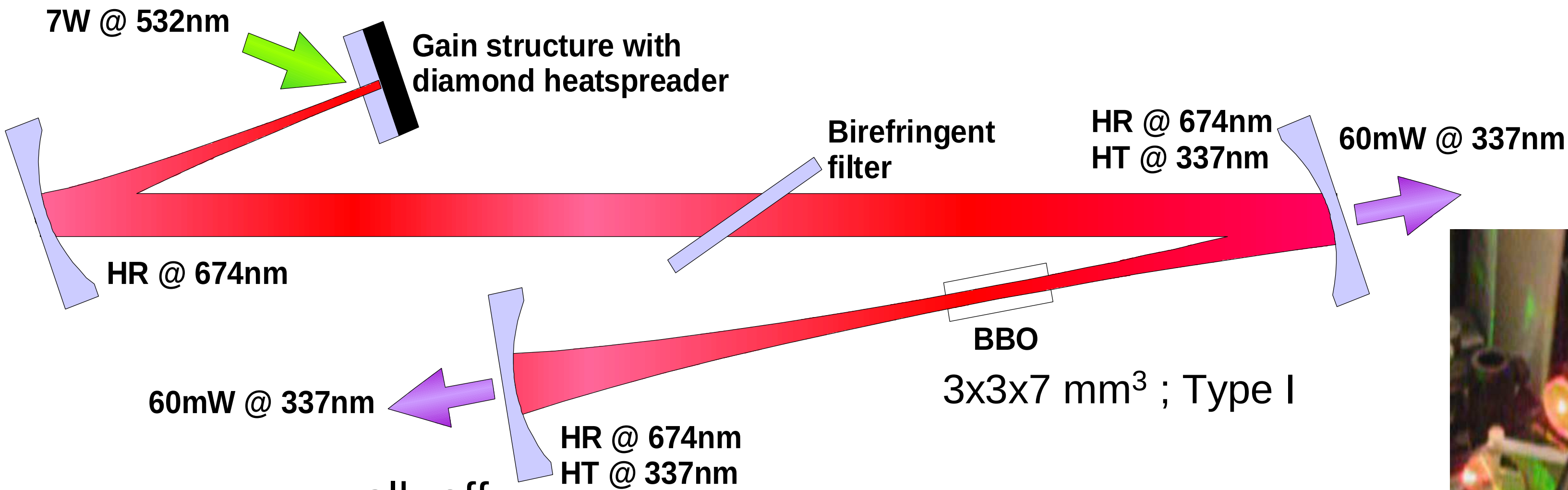

INSTITUTE OF PHOTONICS

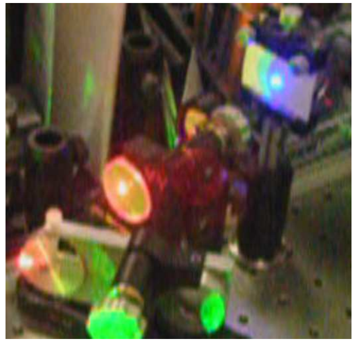
Jennifer Hastie

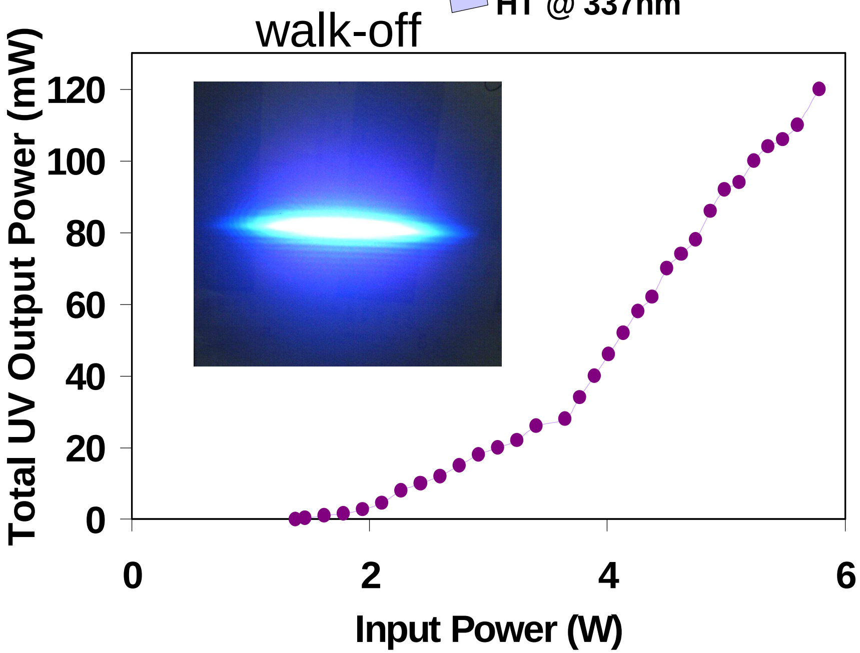
Martin Dawson

- Introduced at Sandia (sapphire) by Alford et al (2002)
- Institute of Photonics, University of Strathclyde extended the technique to SiC, diamond, from 2003
- chip is left intact
- heatspreader functions as intracavity etalon
- monolithic microchip device, lens array…

# *Red VECSEL frequency doubled to ultraviolet*



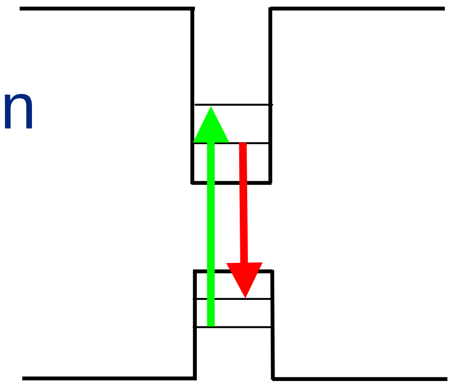


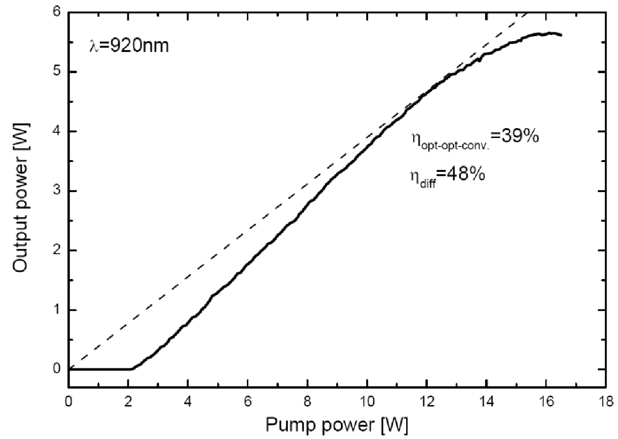

- **<u>120mW</u> @ 337nm**
- **<u>5nm</u> tuning range**
- **Green ⇨ UV efficiency ~2%**
- **Elliptical Gaussian beam**

*Hastie et al., Appl. Phys. Lett 2006*

# In-well pumping

- pump light absorbed only in the wells, not the barriers
- small quantum defect and reduced thermal load
- low absorption efficiency overcome by sub-cavity design
- 808-nm pump, 920-nm laser
- >5 W output power at 39% optical/optical conversion efficiency

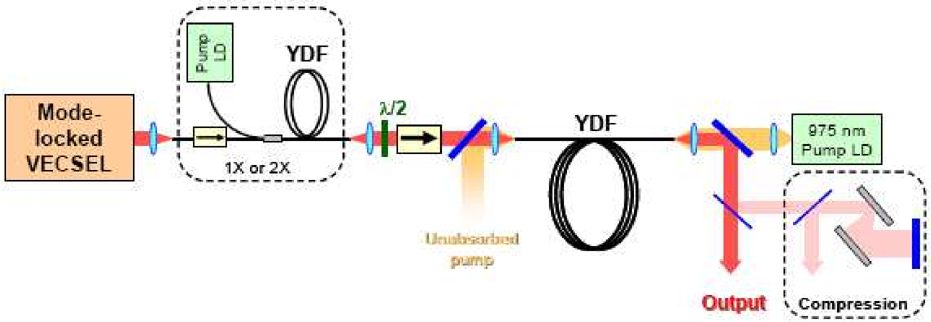


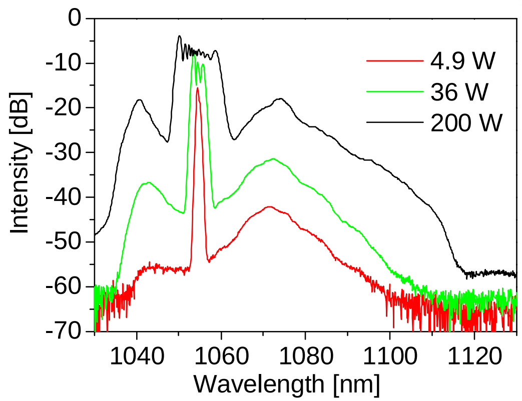



Stefan Lutgen
CLEO 2005

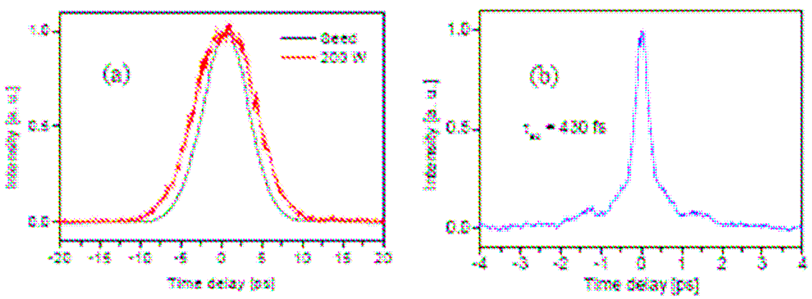
# 200-W VECSEL-YDFA

with:
Pascal Dupriez
Johan Nilsson
Andy Malinowski
David Richardson
Southampton ORC



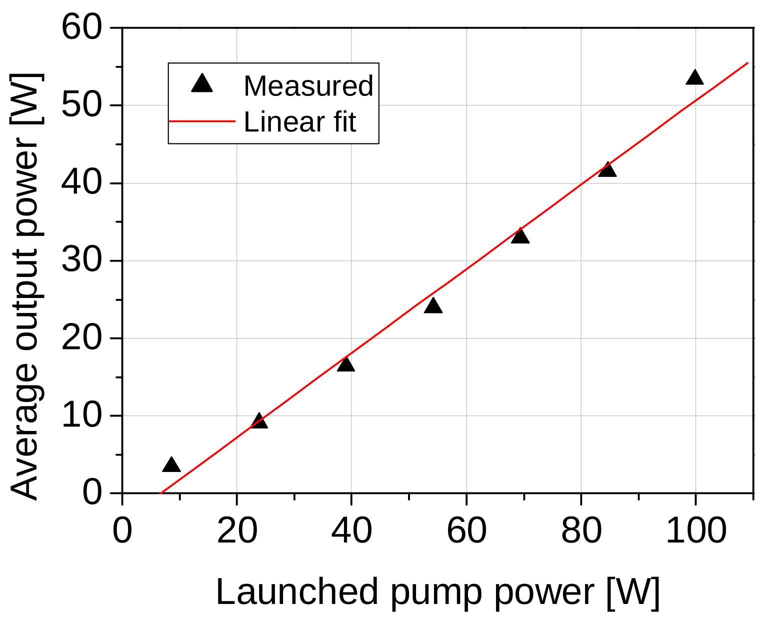

- ➔ Stable 1055-nm 8-mW 4.6-ps VECSEL MO for Yb-doped fibre power amplifier
- ➔ 200-W average power output in 6.3-ps 910-MHz pulse train
- ➔ 220 nJ, 35 kW

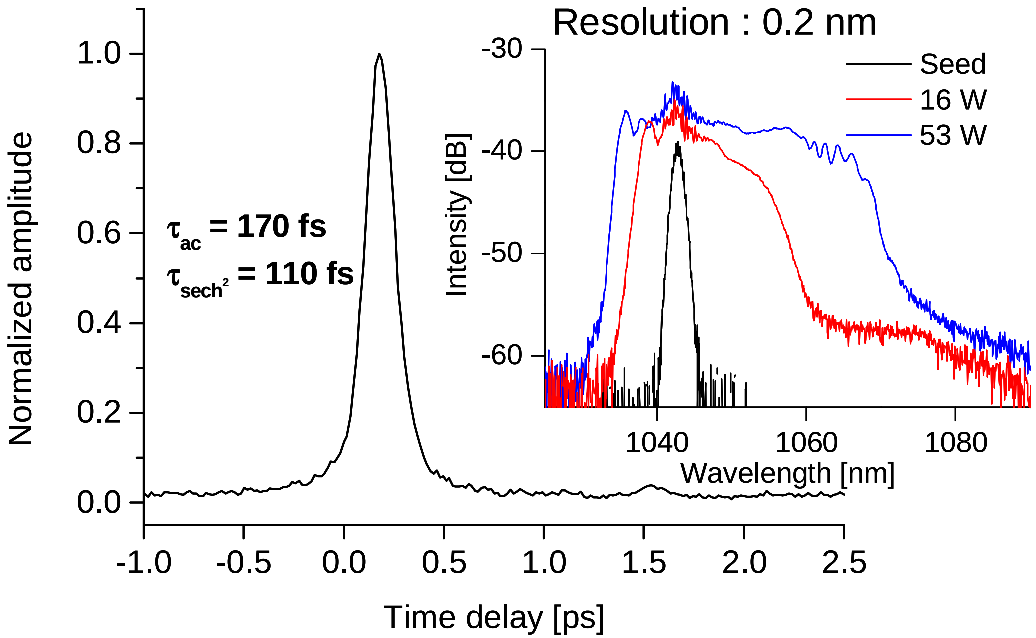



Dupriez et al. CLEO 2006

# 50 W, 110 fs VECSEL-YDFA

- 500-fs 2-nm pulses into small core fibre amplifier
- parabolic regime: exponential growth of $\Delta\lambda$ and $\tau$
- clean linearly-chirped pulse
- re-compress to 110 fs




Dupriez et al. Optics Express 2006

# Conclusions

- VECSELs potentially the most versatile of all solid state lasers
- unprocessed wafers generate 400 mW cw power, or 50 W peak – optical Stark mode-locking technique
- thermal management $\rightarrow$ 100 W regime in a modular device
- diamond heatspreader accesses 'difficult' wavelengths; red, UV, mid-IR…
- VECSEL-YDFA extends average power $\rightarrow$ 200 W, peak power $\rightarrow$ 35 kW