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Kemp, A. and Hastie, J.E. and Hopkins, J.M. and Calvez, S. and Dawson, M.D. and Burns, D. and Holt, T. (2007) *Semiconductor disk lasers: the future's bright; the colour's flexible.* In: The Industrial Laser Users, 1900-01-01.

Kemp, A.* and Hastie, J.E. and Hopkins, J.M. and Calvez, S.* and Dawson, M.D.* and Burns, D.* and Holt, T (2007) Semiconductor disk lasers: the future's bright; the colour's flexible. In: The Industrial Laser Users.

Semiconductor Disk Lasers: The Future's Bright; The Colour's Flexible.

St. Andrews / Heriot-Watt M.Sc.: Industrial Lecture Series

Alan Kemp, Alex Maclean, Rolf Birch, Lynne Morton, Stephanie Giet, Patsy Millar, John-Mark Hopkins, Jennifer Hastie, Stephane Calvez, Martin Dawson and David Burns.

Institute of Photonics, University of Strathclyde, Glasgow.
www.photonics.ac.uk

The Institute of Photonics

- Set-up in 1996 to help bridge the gap between academia and industry
- Research-only unit within the University of Strathclyde
- ~1/3 funding from EPSRC etc; ~1/3 directly from Industry; ~1/3 from joint schemes
- ~50 people from 9 countries including 24 PhD/EngD students

- 4 research teams:
  - Semiconductor Optoelectronics: Materials, VCSELs, VECSELs, μLEDs …
  - GaN growth: MOCVD, processing, device fab, microcavities …
  - Applications of Photonics: dental diagnosis, microscopy, spectroscopy …
  - Solid-State Lasers: solid-state lasers, mid-IR lasers, Adaptive Optics …

Outline

- What are Semiconductor Disk Lasers?
  - How do they work?
  - Are they important?
  - What are they good at?

- How can they be used?
  - High speed internet in cities
  - Laser projection TV
  - Finger print detection

What are Semiconductor Disk Lasers?

Semiconductor Disk Lasers

A hybrid diode-pumped solid-state / semiconductor laser

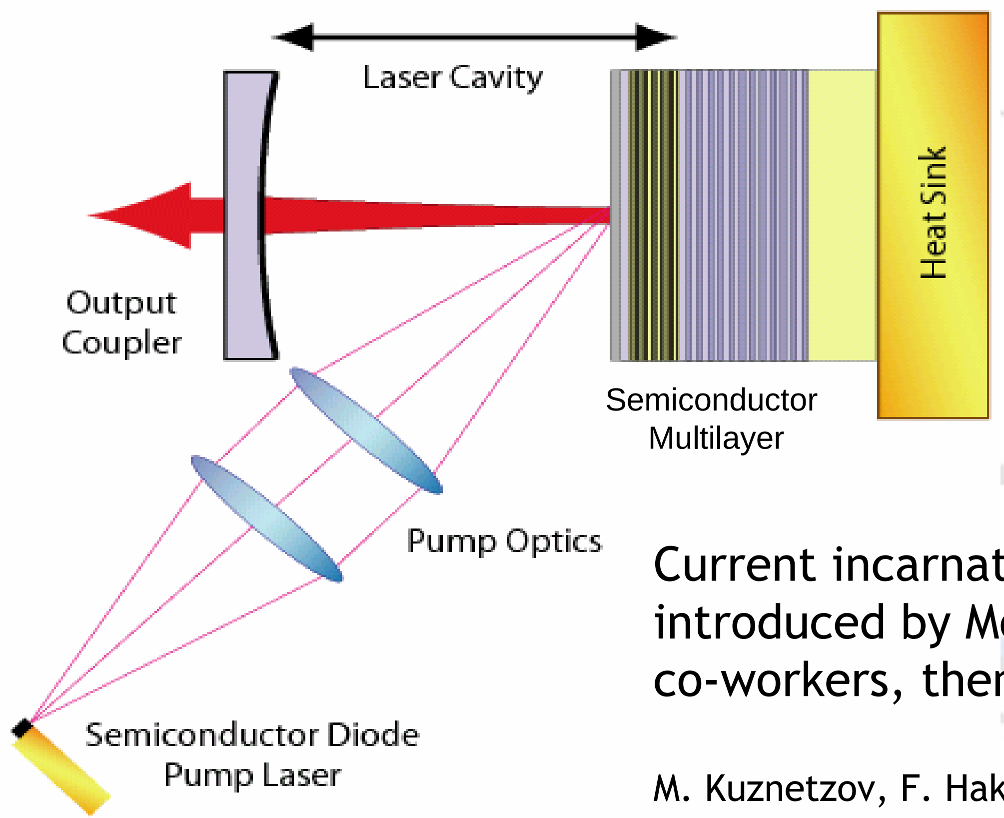
Vertical
External
Cavity
Surface
Emitting
Laser

or

Optically-
Pumped
Semiconductor
Laser

or

Semiconductor Disk Laser



Current incarnation introduced by Mooradian and co-workers, then at Micracor

M. Kuznetzov, F. Hakimi, R. Sprague, and A. Mooradian, IEEE J. Select. Top. Quantum Electron., **5**, 561-573 (1999).

Semiconductor laser perspective

Edge Emitting Laser Diodes and
Vertical-cavity Surface-emitting Lasers (VCSELs)

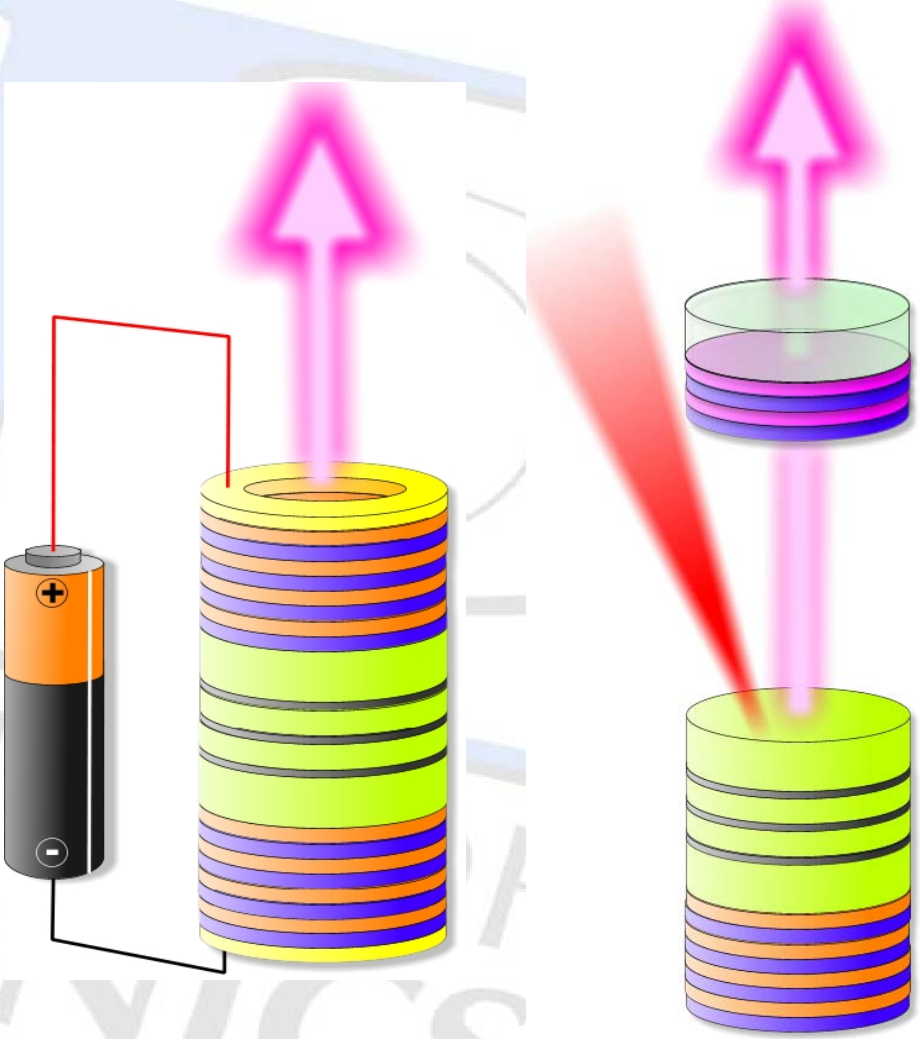
Both:	Cheap and Compact
	Electrical injected - convenient
	Complex structure due to current injection
Edge:	High Power (Ws to kWs (arrays))
	But.. Poor beam quality (esp. for high power)
VCSEL:	Good beam quality
	But.. Low power! (few mW)

High Power *OR* Good Beam Quality

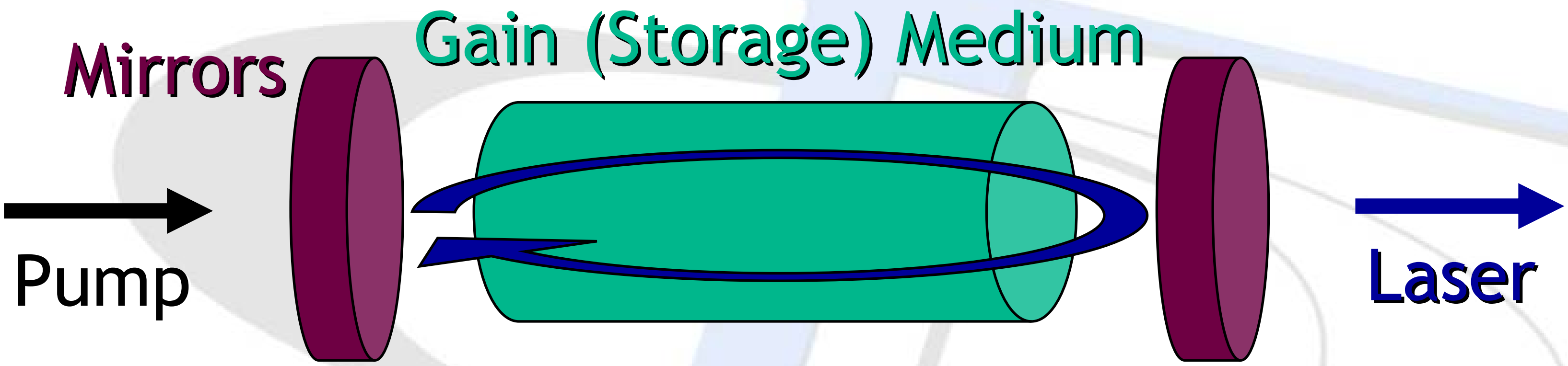
Semiconductor Disk Laser

Take a VCSEL:

1. Remove electrical contacts
   - Easier design, no doping
2. Move to optical pumping
   - No current spreading issues for beam quality
3. Remove top mirror;
   Add external cavity
   - Mode control
     - Good beam quality
   - Flexibility
     - Modelocking
     - Frequency doubling
     - Single frequency
4. High Power, Good Beam Quality



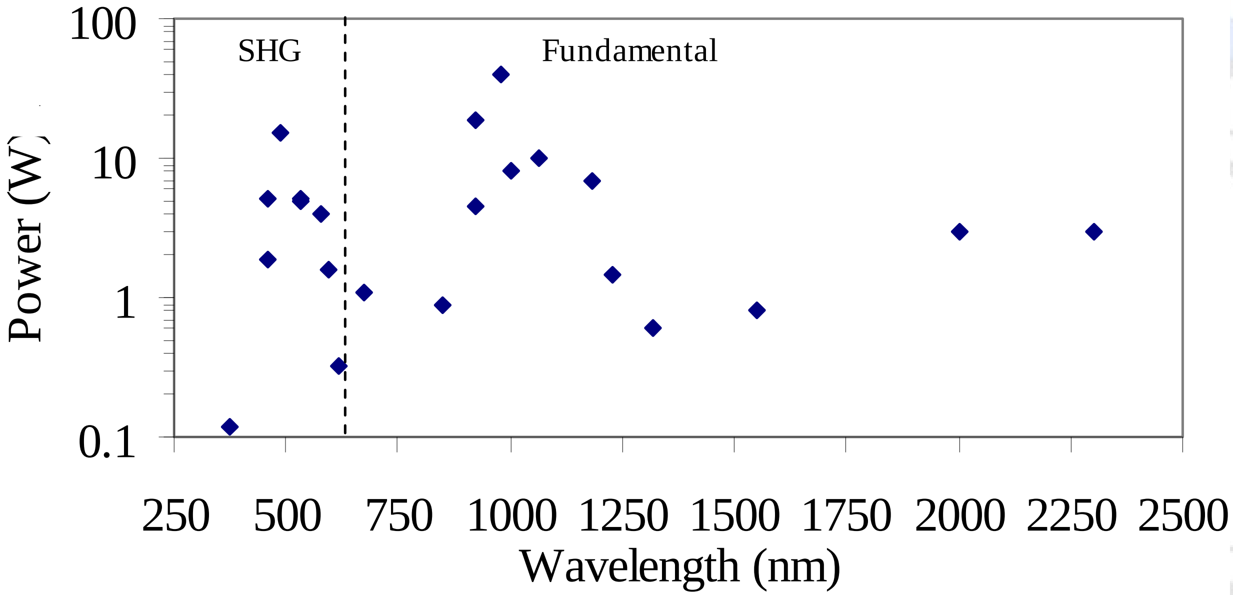
Solid-state laser perspective



- High power/energy, good beam quality, short pulses, single frequency etc…
- BUT, stuck with the wavelengths provided by doped crystals:
  - Nd:YAG (946nm, 1064nm, 1320nm etc)
  - Ti:Sapphire (~700 to ~1100nm)
  - Yb:YAG (~1030nm)

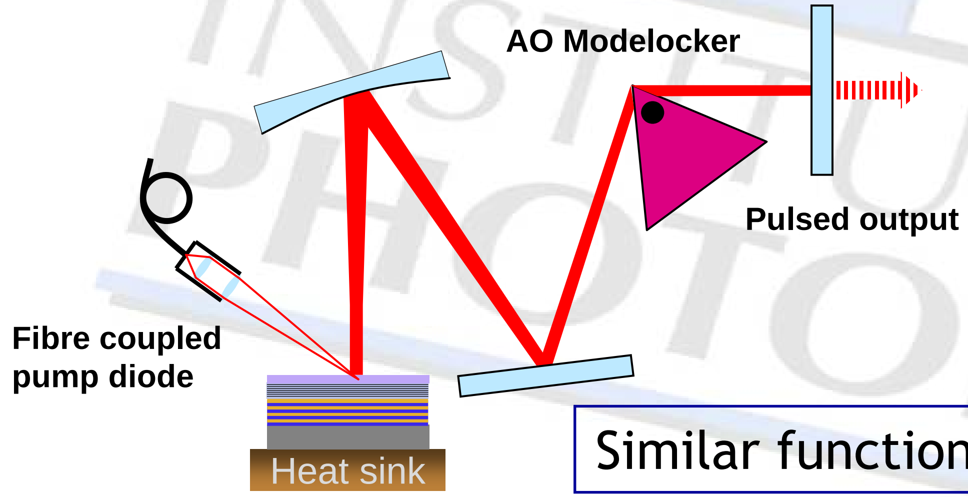
Exceptional functionality ***BUT*** limited spectral coverage

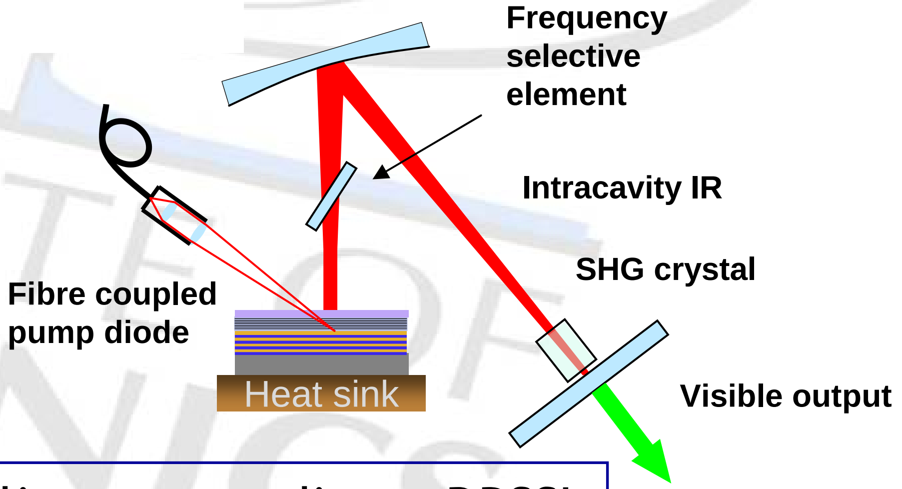
Semiconductor Disk Laser



Wavelength can be engineered:
Potentially from ~650nm to 2500nm (to ~330nm with SHG)

Each device tuneable over 10-100nms





Similar functionality to an ordinary DPSSL

Drawbacks

Semiconductor laser perspective:

- Not generally electrically pumped (although they can be)

  Less convenient

- External cavity required

  Less robust

Solid-state laser perspective:

- Don’t store energy well

  Poor sources of high energy pulses

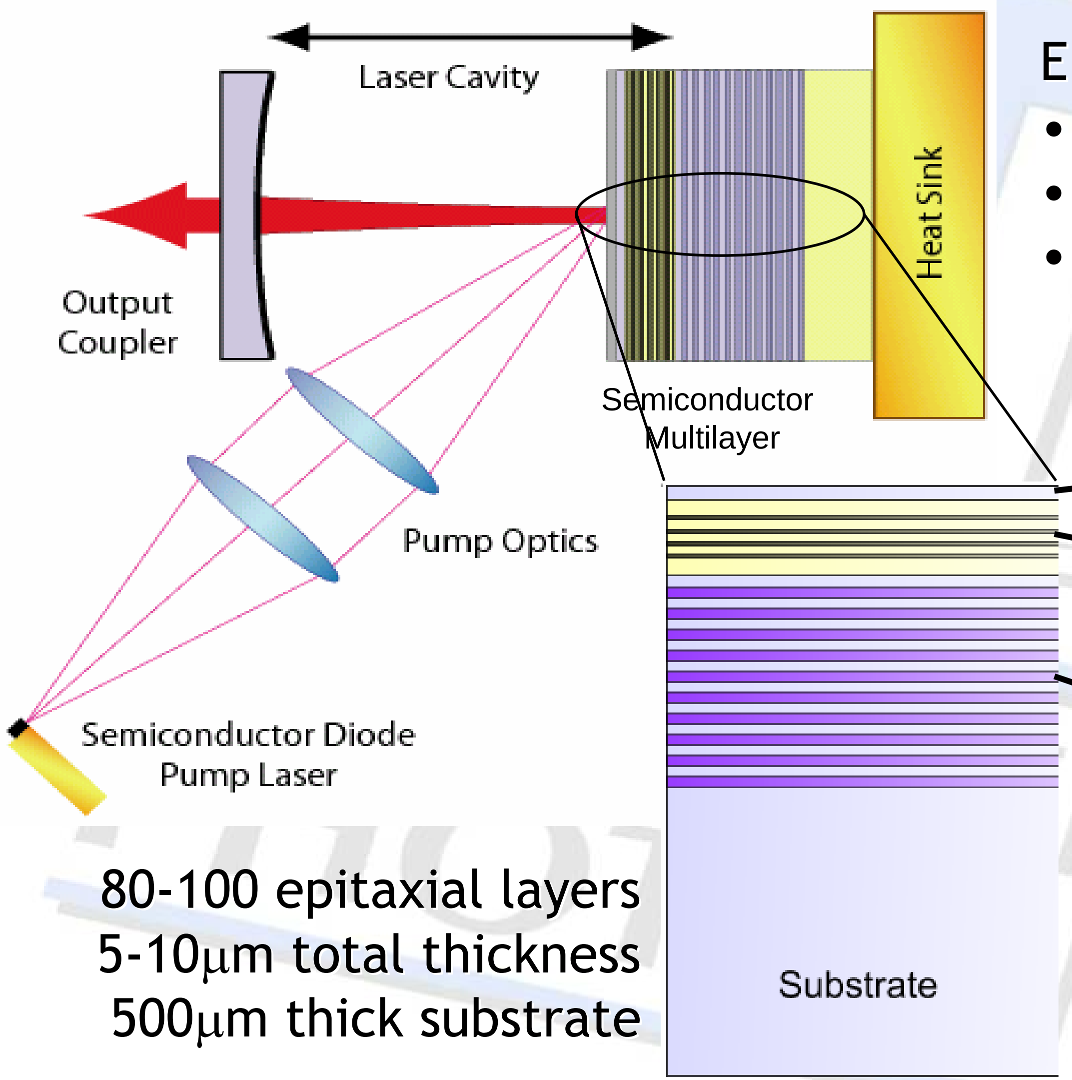
- Thermally sensitive

  Need to take care with heat management

However, as wavelength engineerable diode-pumped solid-state lasers, Semiconductor Disk Lasers allow the laser to be tailored to the application

How do they work?

Deconstructing the Disk Laser



Elements:
- Pump system
- External cavity
- Semiconductor multilayer

Window/Cap

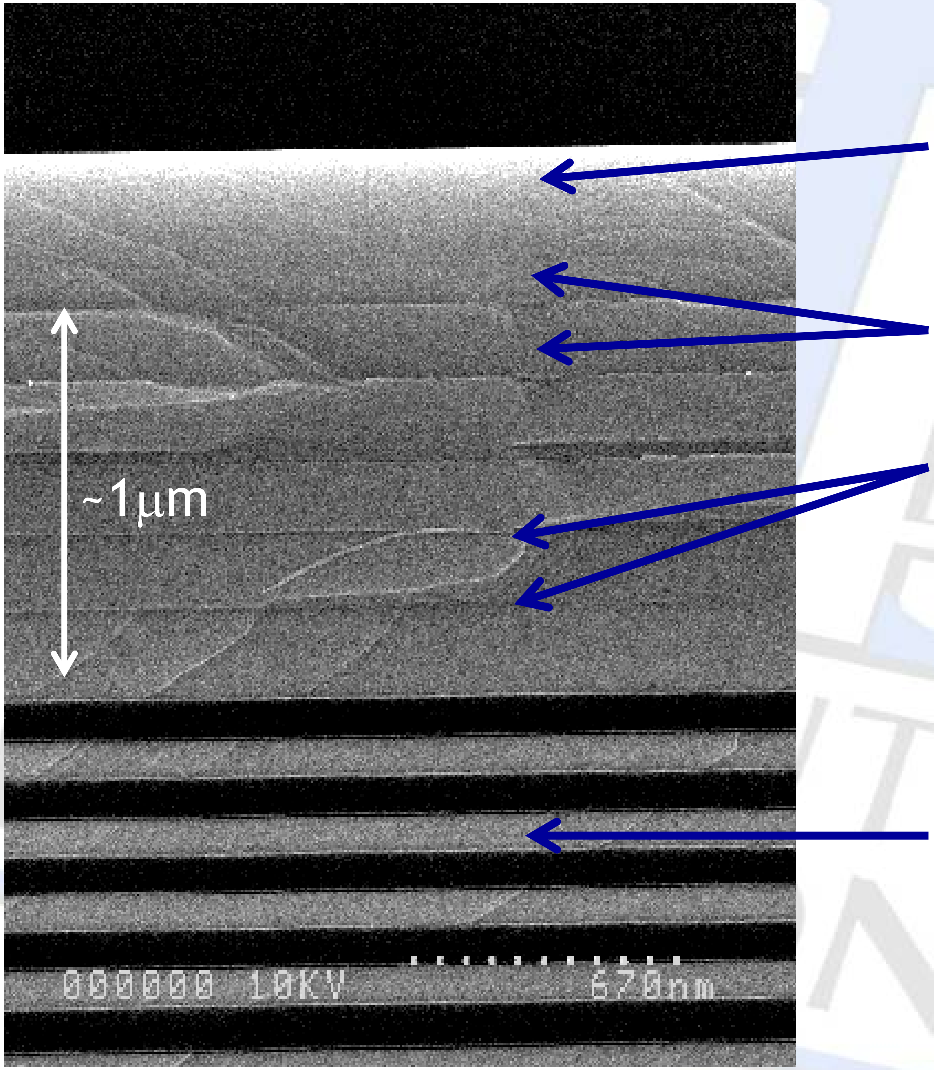
Quantum Wells and Barriers

Distributed Bragg Reflector (DBR)

80-100 epitaxial layers
5-10μm total thickness
500μm thick substrate

Grow as a ~3” wafer and dice up into 100’s of lasers
Cheap in bulk

Scanning Electron Micrograph



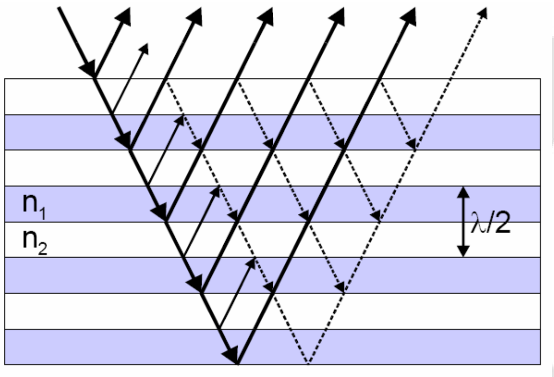
Window / cap

Barriers

Quantum Wells

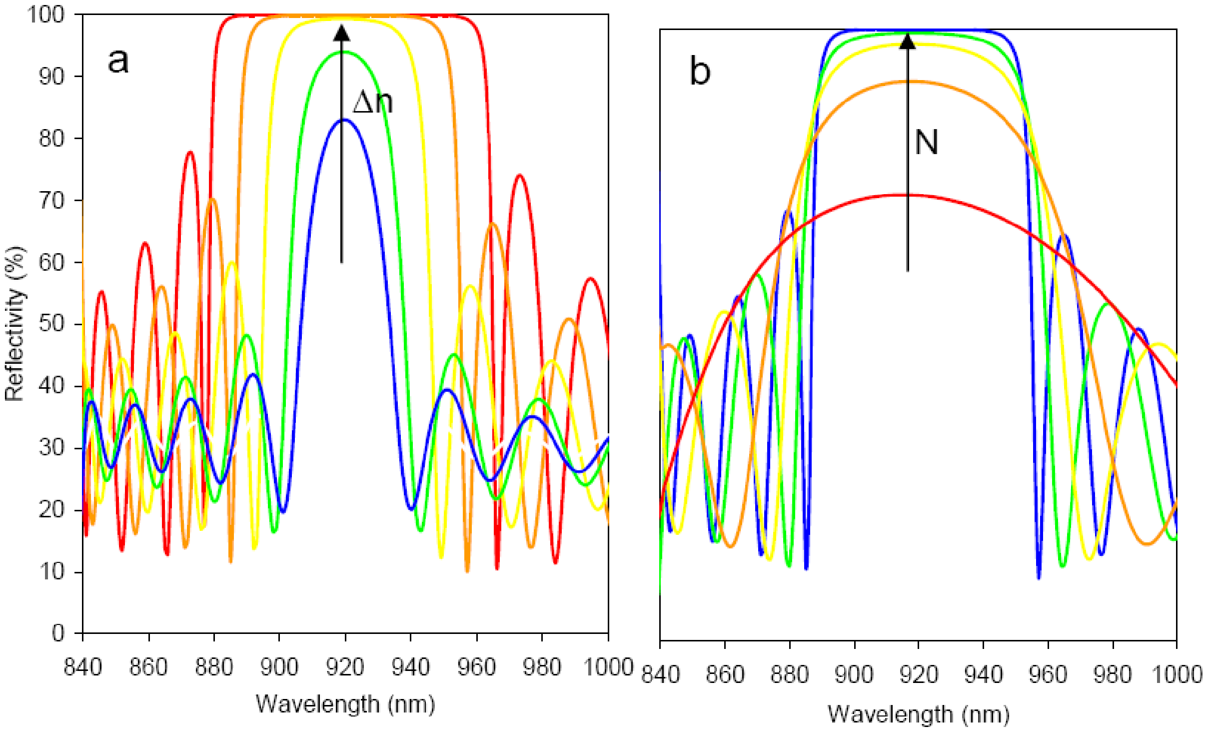
First few layers of the Distributed Bragg Reflector

Distributed Bragg Reflector (DBR)



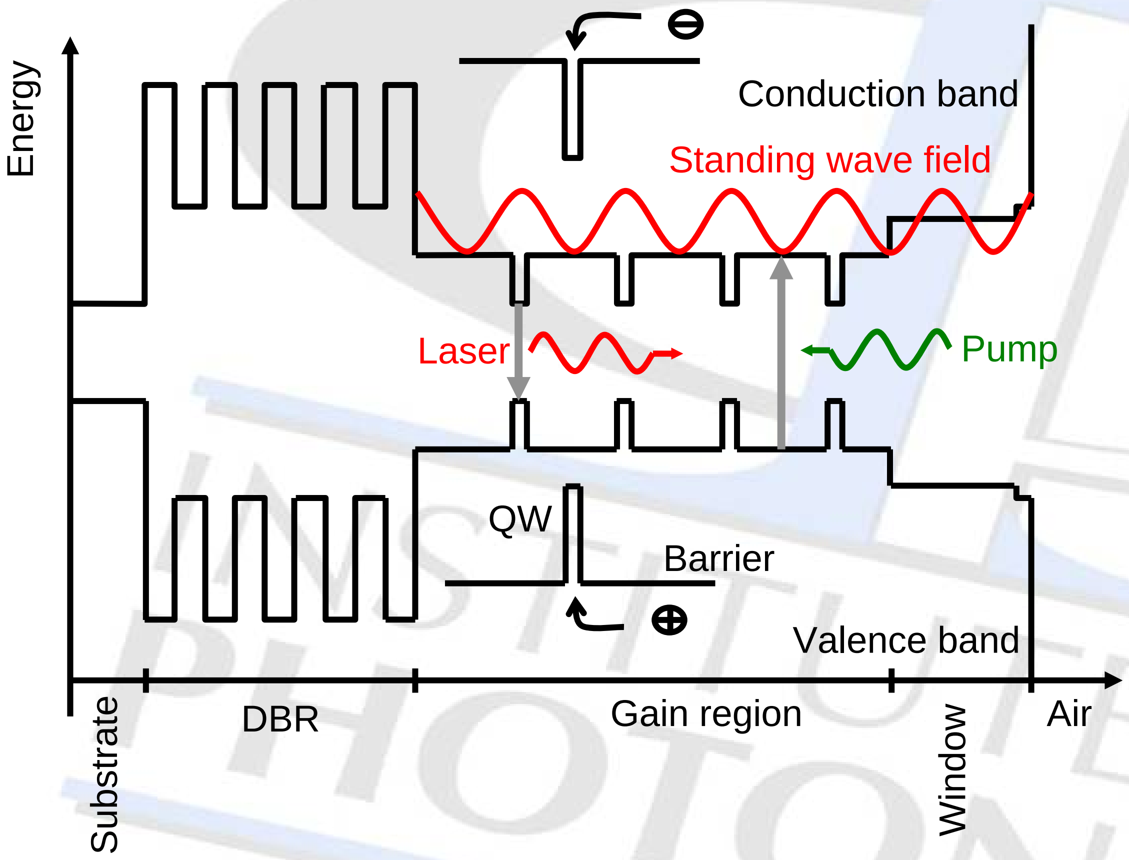
High and low refractive index layers λ/4 thick cause reflections to add in phase to give a high reflectivity mirror

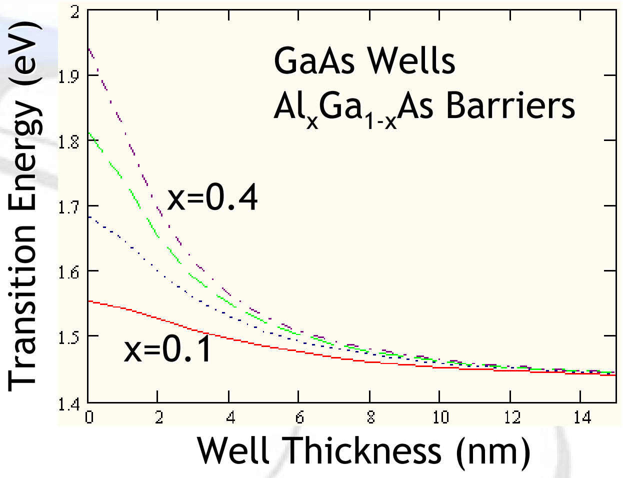
- Larger index contrast (Δn)
  - ✓higher reflectivity and bandwidth
  - ×not always possible due to lattice matching / transparency
- More layer pairs (N)
  - ✓higher reflectivity
  - ×narrower bandwidth
  - ×longer growth time

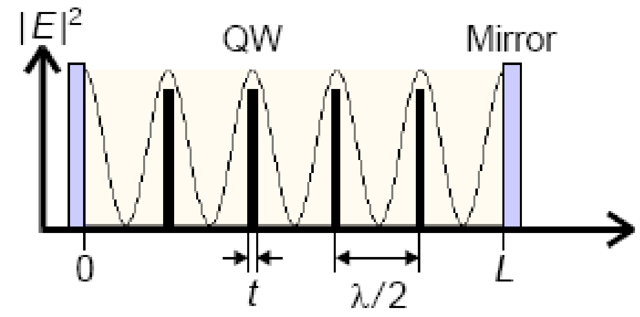


~30 pairs of high and low refractive index layers: e.g. GaAs (~3.5) and AlAs (~3.0) for around 1μm

Gain: wells and barriers





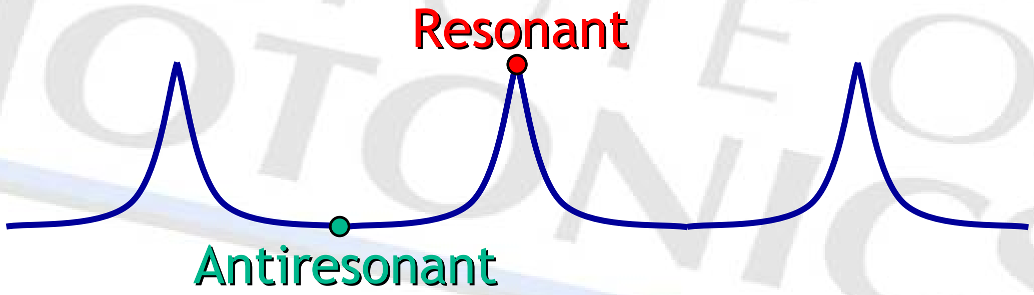


“Resonant Periodic Gain” (RPG)

Window prevents carrier recombination at the surface

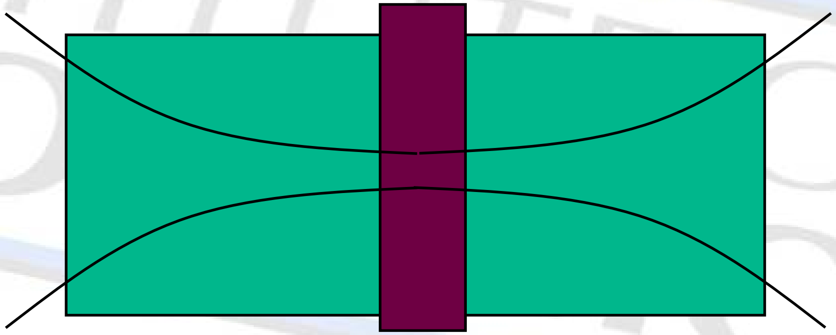
Design options

- Barrier material/height: min pump wavelength
- Well material/width/barrier height: laser wavelength
- Well position relative to the standing wave field and pump absorption
- Resonant / antiresonant subcavity: threshold v. bandwidth

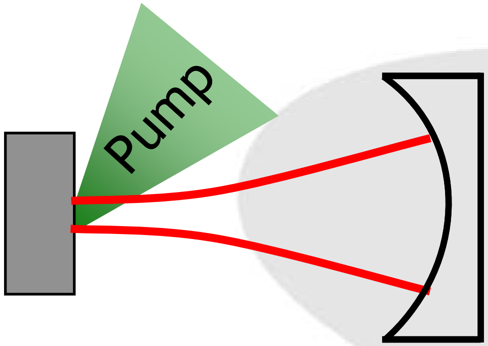


Laser Properties

- High gain / short lifetime (ns): similar threshold to doped-dielectric
- Short lifetime (ns): poor energy storage, poor q-switching
- Broad gain bandwidth: 10-100nm tuning
- Temperature sensitive: gain and subcavity resonance
- Very short pump absorption length (~1μm) – insensitive to pump quality

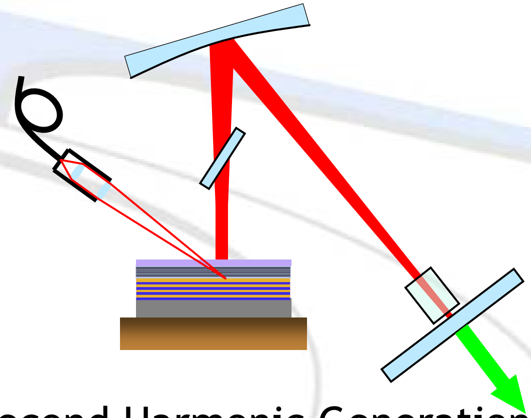


External cavity

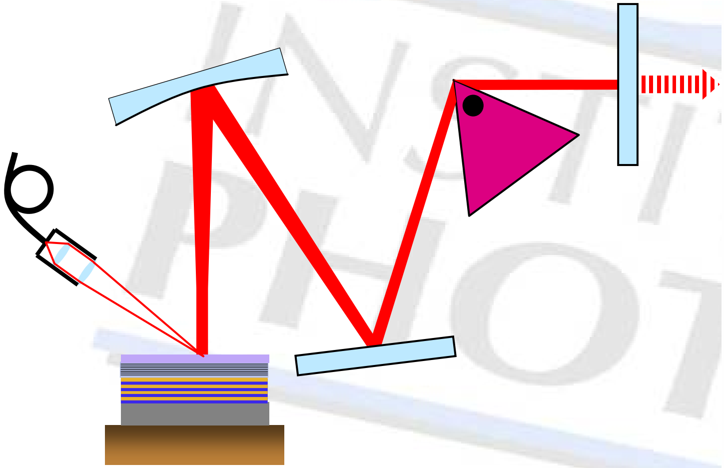


- Adjust cavity so that laser and pump mode match
- Improved beam quality

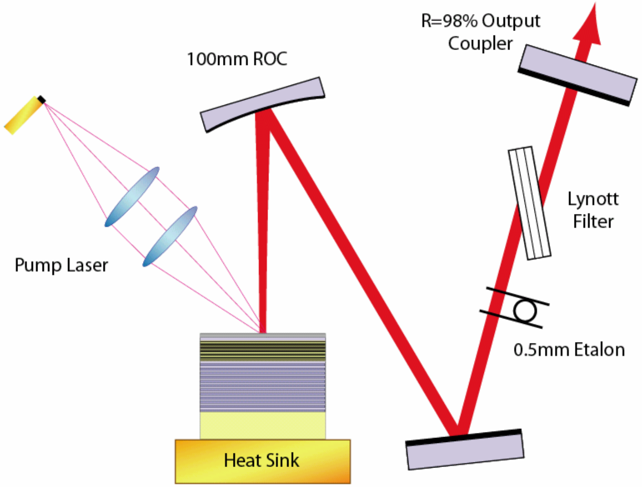
Use cavity to permit extra a functionality not typical of semiconductor lasers:



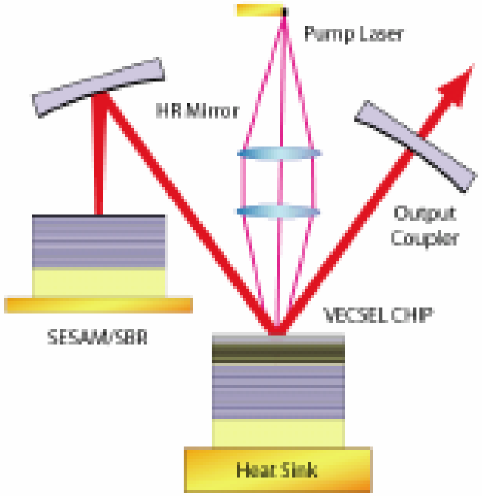
Second Harmonic Generation



Active Modelocking



Single Frequency



Passive Modelocking

Pumping

- Short pump absorption length (~1μm, c.f. ~1mm for Nd:YAG)
  - Pump doesn't need to be as bright

- Pump photon energy just needs to be larger than barrier bandgap energy
  - Can choose any available pump with this or a shorter wavelength
  - Can pump with high power diode lasers
    - Engineer for use with high power pumps
  - No need to temperature control pump diodes (c.f. <1°C for Nd:YAG)

What are they good at?
What's the bad news?

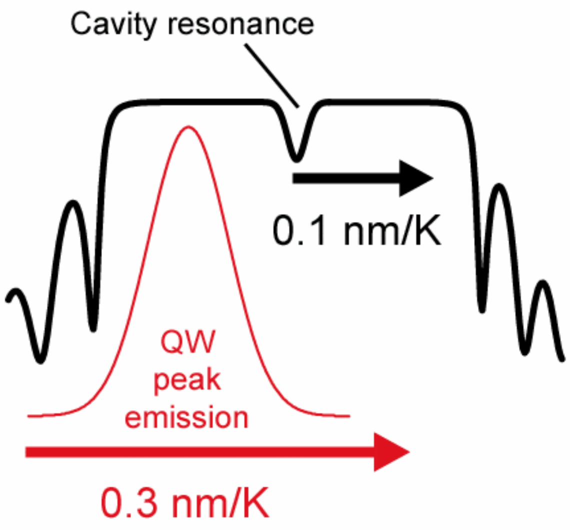
Issues in Se/c Disk Lasers

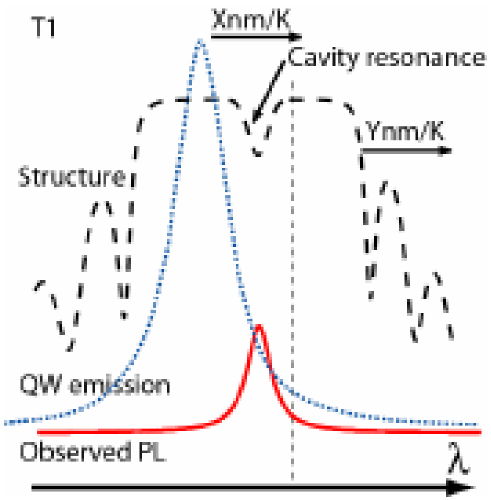
Challenges and Opportunities:

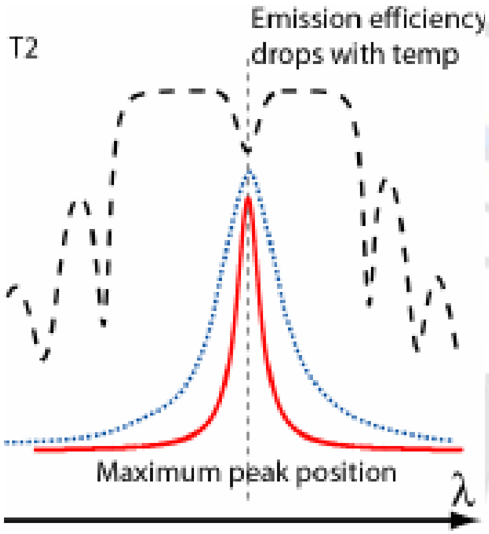
- Thermal Management
- Wavelength Control and Spectral Coverage
- Electrical Injection
- Output Control
  - Second Harmonic generation
  - (Wavelength tuning)
  - (Single frequency operation)
  - (Modelocking)
- Comparison with Nd:YAG and Ti:Sapphire

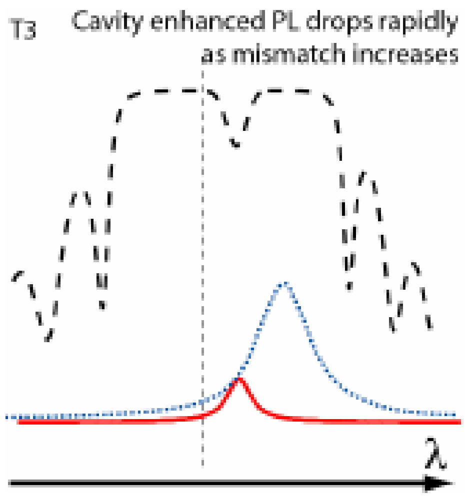
Thermal effects

- Temperature increases with pump power:
  - Temperature dependent gain
    - Recombination processes
    - Carrier leakage out of wells
  - Thermal expansion, bandgap & refractive index change
  - QW peak gain and sub-cavity resonance shift at different rates

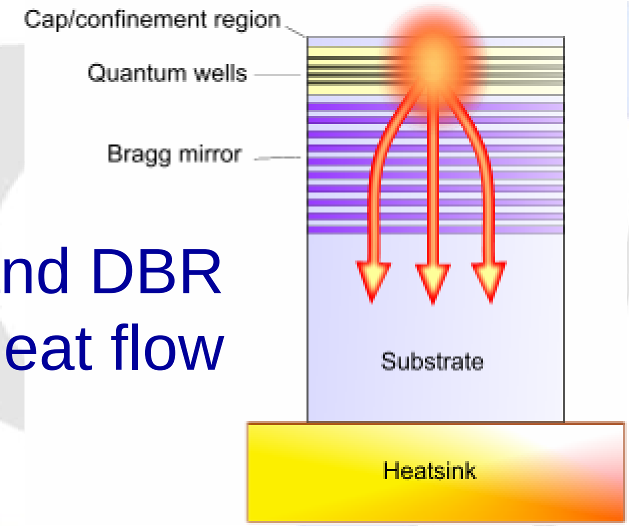




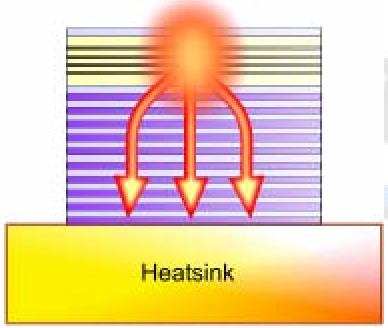




Thermal Management

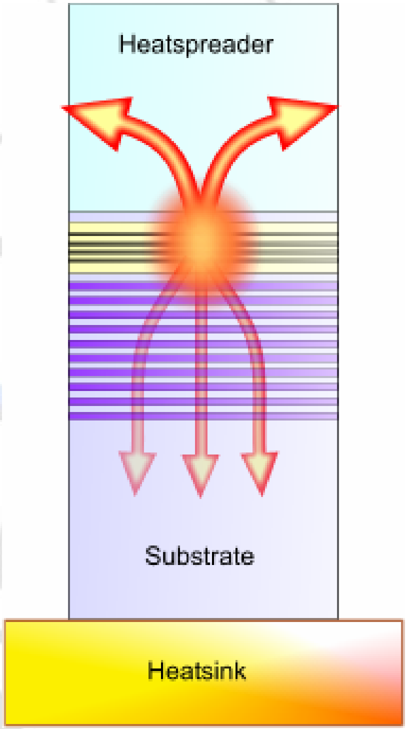


Substrate and DBR impede heat flow



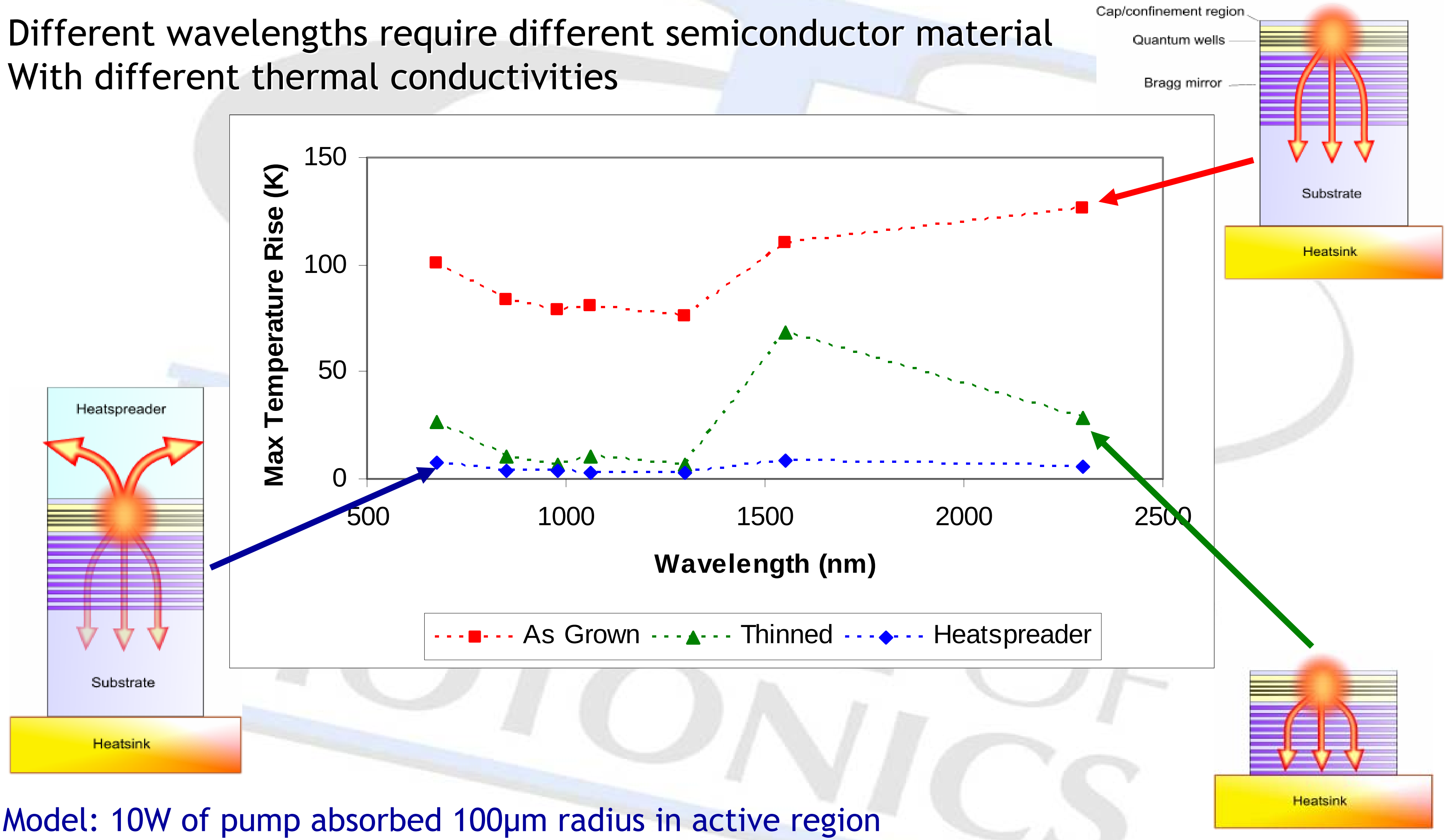
Thin Device
Remove Substrate

Heatspreader
Add high conductivity crystal



Thermal Management

Different wavelengths require different semiconductor material
With different thermal conductivities



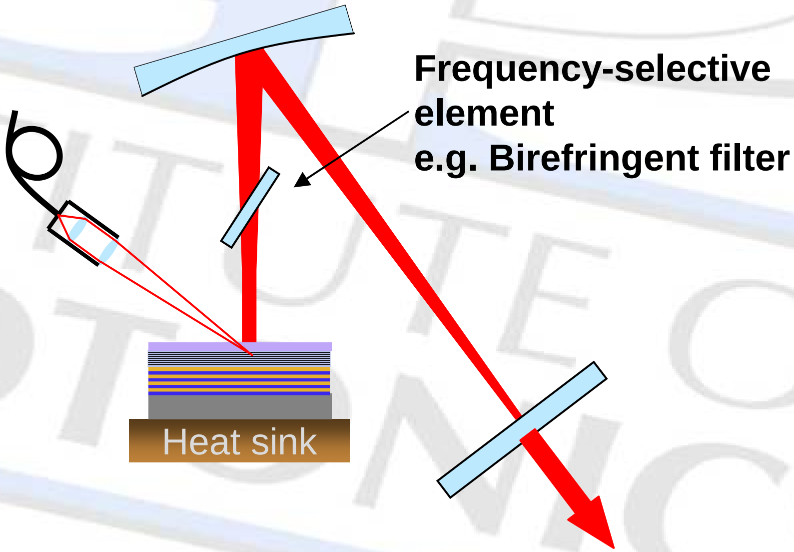
Model: 10W of pump absorbed 100μm radius in active region

Wavelength Control / Tuning

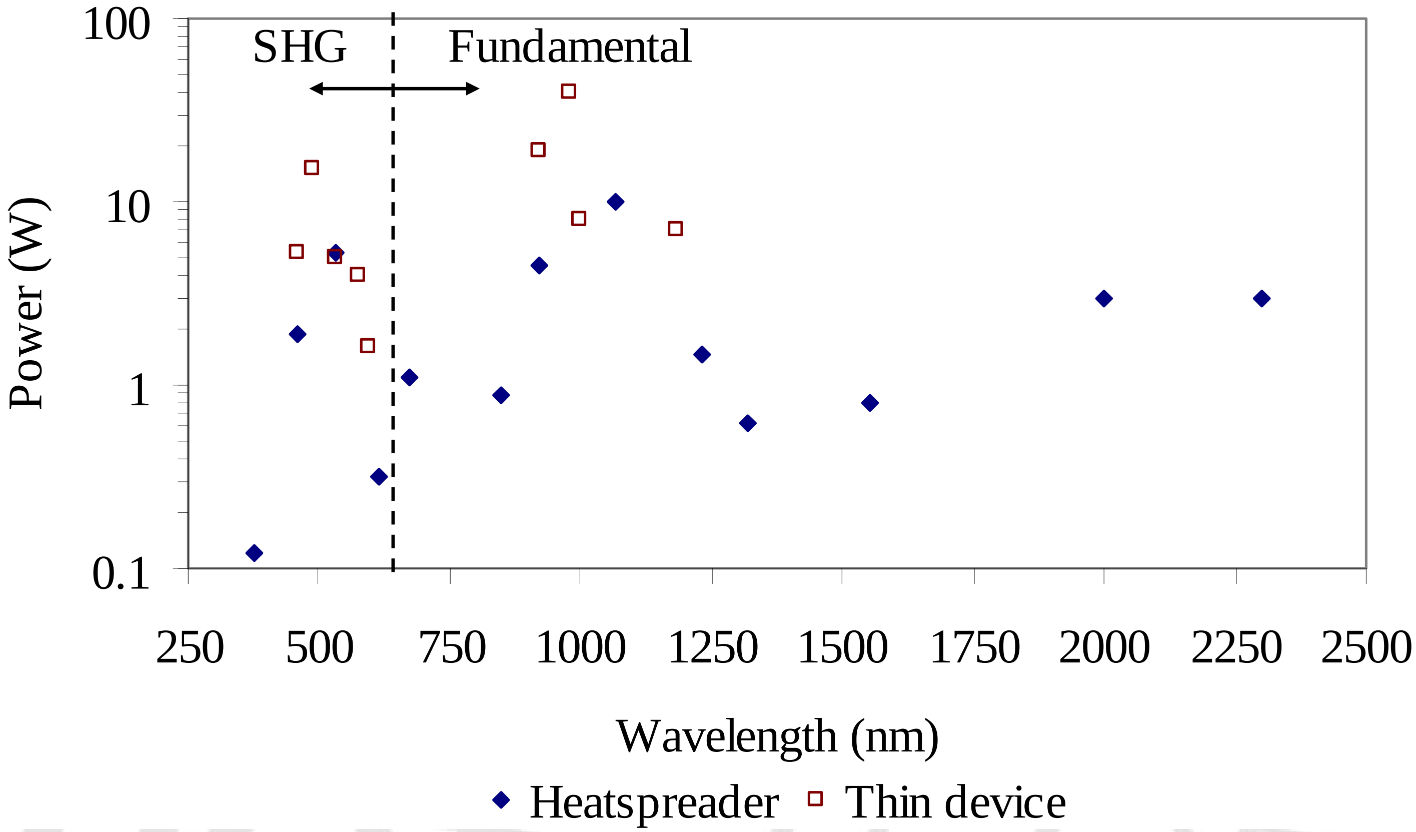
- Broad gain bandwidth (~10nm) c.f. Nd:YAG (~1nm)

- Need intracavity wavelength control to maintain wavelength of choice
- Need spectral control for narrow linewidth applications like SHG
- Can tune of 10-100nm

- Some built in control with sub-cavity
- Heatspreaders – usually broader spectra – often need extra control



Spectral coverage

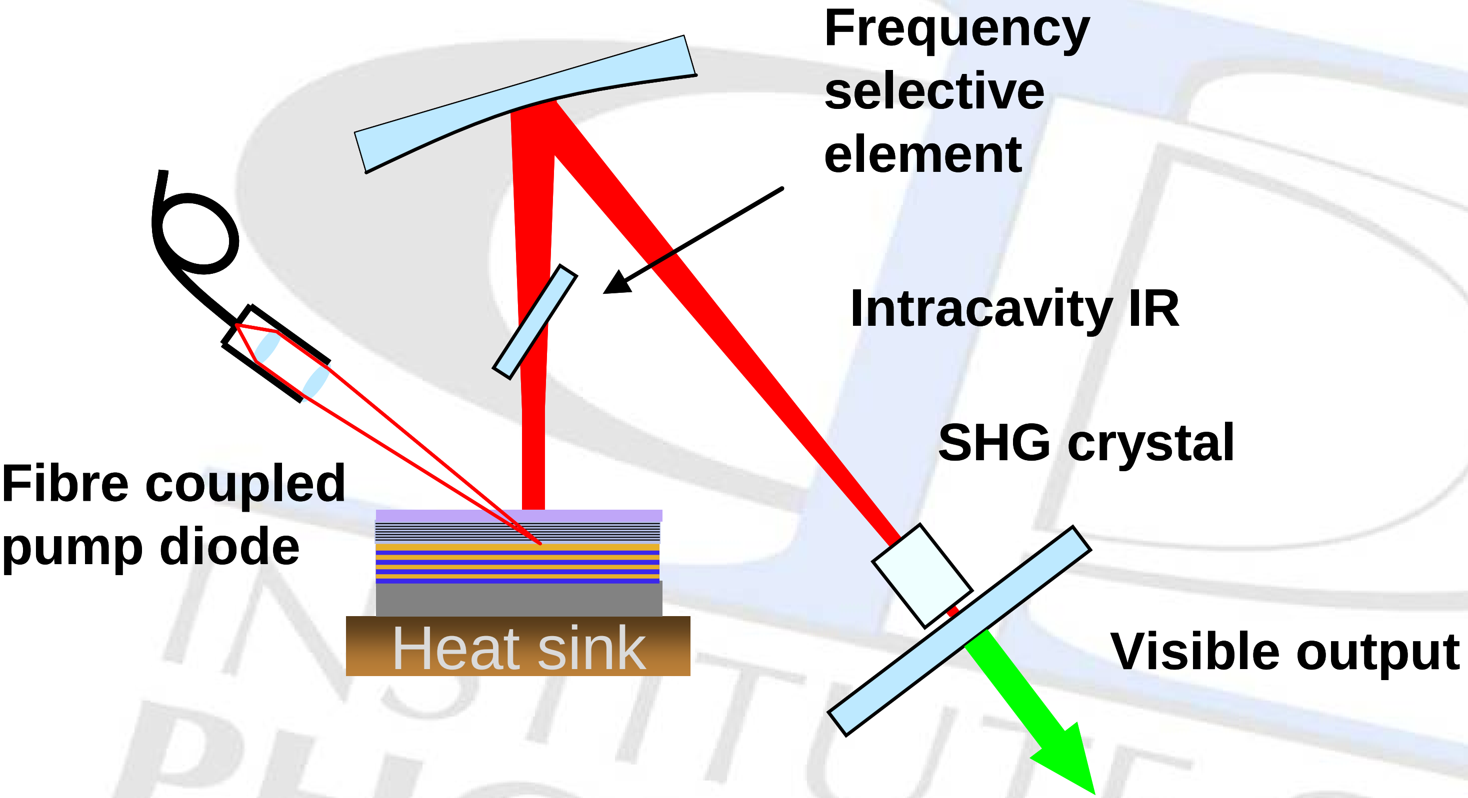


- High powers demonstrated from 670-2200nm
- Down to 340nm with intracavity SHG
- Heatspreaders enable improved wavelength coverage

Electrical Injection

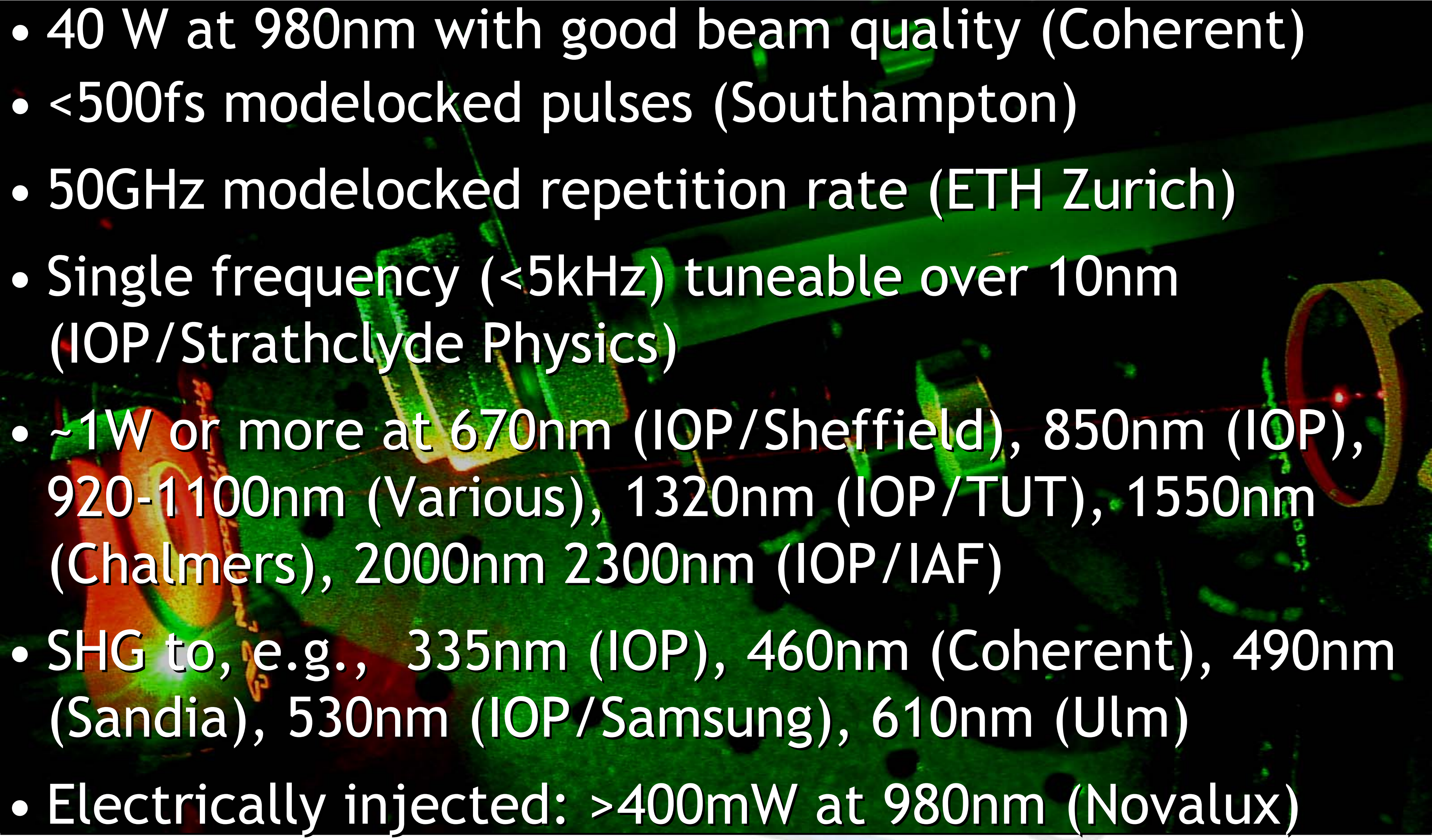
- Demonstrated by Novalux
- >400mW at 980nm, good mode
- Main difficulty is uniform current injection
- Structure more complicated and losses higher than optical pumping
- So far just at wavelengths of ~1μm (and second harmonic)
- Also modelocking and SHG

Second harmonic generation



- 15W at 488nm (Coherent)
- Also 335, 460, 530, 610nm (various)
- Performance much as solid-state laser BUT lower cost, smaller
- Wavelength control required

SDLs: the state of the art



- 40 W at 980nm with good beam quality (Coherent)
- <500fs modelocked pulses (Southampton)
- 50GHz modelocked repetition rate (ETH Zurich)
- Single frequency (<5kHz) tuneable over 10nm (IOP/Strathclyde Physics)
- ~1W or more at 670nm (IOP/Sheffield), 850nm (IOP), 920-1100nm (Various), 1320nm (IOP/TUT), 1550nm (Chalmers), 2000nm 2300nm (IOP/IAF)
- SHG to, e.g., 335nm (IOP), 460nm (Coherent), 490nm (Sandia), 530nm (IOP/Samsung), 610nm (Ulm)
- Electrically injected: >400mW at 980nm (Novalux)

How the performance compares

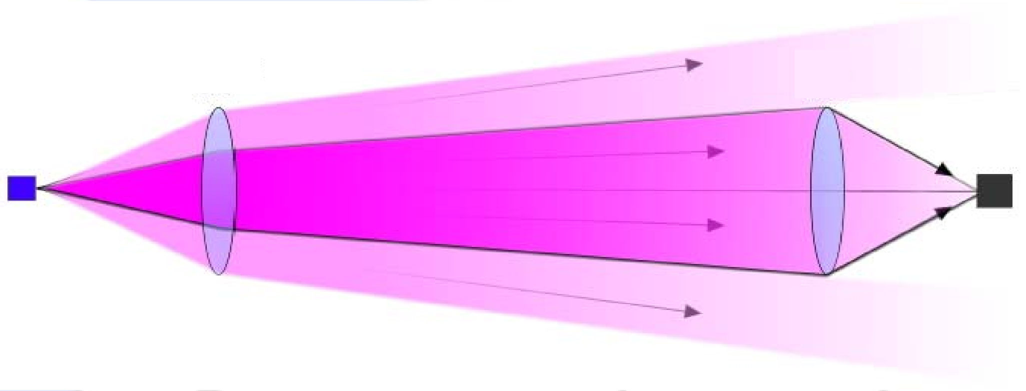
	SDL	Nd:YAG	Ti:S
Output Power (W)	<50	<5000	<20
Output Power, 10W pump (W)	3-4	4-5	1
Peak Output Wavelength (nm)	660-2300	946/1064/1320	790
Tuning (nm)	~10-100	~1	~500
Elec. to Opt. Efficiency (%)	20	30	<5
Modelocked pulse duration (ps)	1	10	<0.01
Q-sw pulse energy, 10W pump	<1nJ?	<2mJ	<20μJ
Cost for 5W (k£)	<1?	1-10	10-100

How can they be used?

Applications

- Free space optical communications
- Laser projection TV
- Forensics
- Spectroscopy and remote sensing
- Pumping other lasers

Free-space optical communications



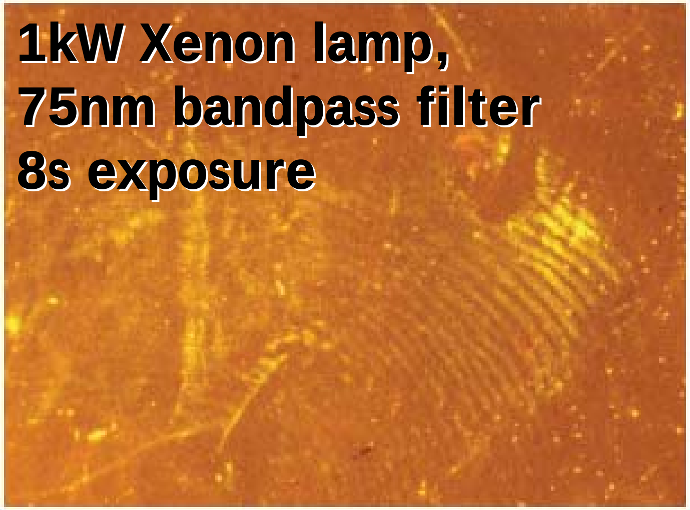
- <5% of businesses have fast fibre link
- 75% within 1 mile of high speed fibre hub
- 2μm atmospheric window
- Can use x50-100 more power @ 2μm
- Some types of (city) fogs transmit better at <3-4μm
- Good detectors at <2.5μm
- Good for adaptive optics
  - Large beam – building sway
  - Small beam - fog

Laser Projection TV: Why?

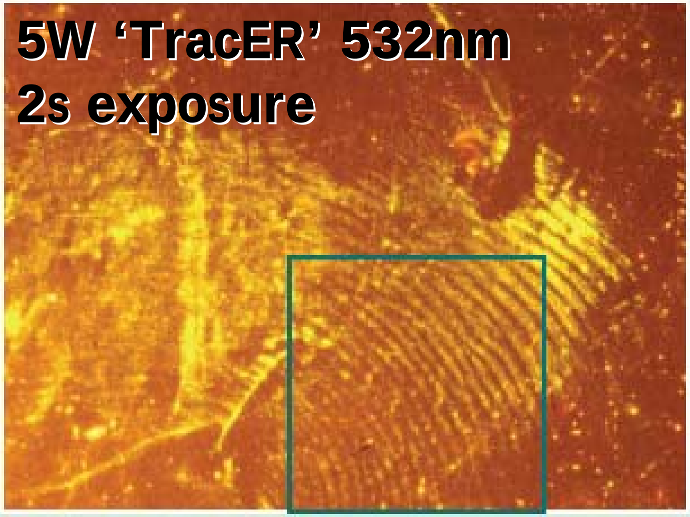
- Better range of ‘true’ colours
    - Design to ‘corners’ of gamut
- Large screen sizes
    - Scanning easier than pixel-by-pixel addressing
- High brightness for outdoors
- Lower power consumption
    - 50” Plasma TV 750W
    - 55” Laser TV 200W(?) (Novalux)
- Semiconductor disk lasers: low-cost, compact route to the ‘right’ wavelengths
- The first mass-market diode-pumped solid-state laser?

Forensics

- 5W hand-held, battery powered!
- Excite natural or dye fluorescence from prints or blood etc; view at longer λ
- More detail / fainter samples with laser



1kW Xenon lamp,
75nm bandpass filter
8s exposure

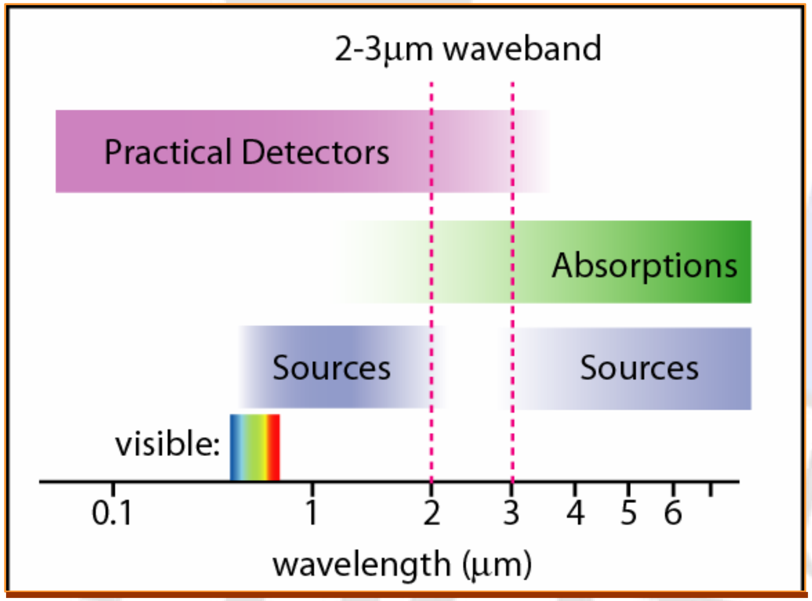


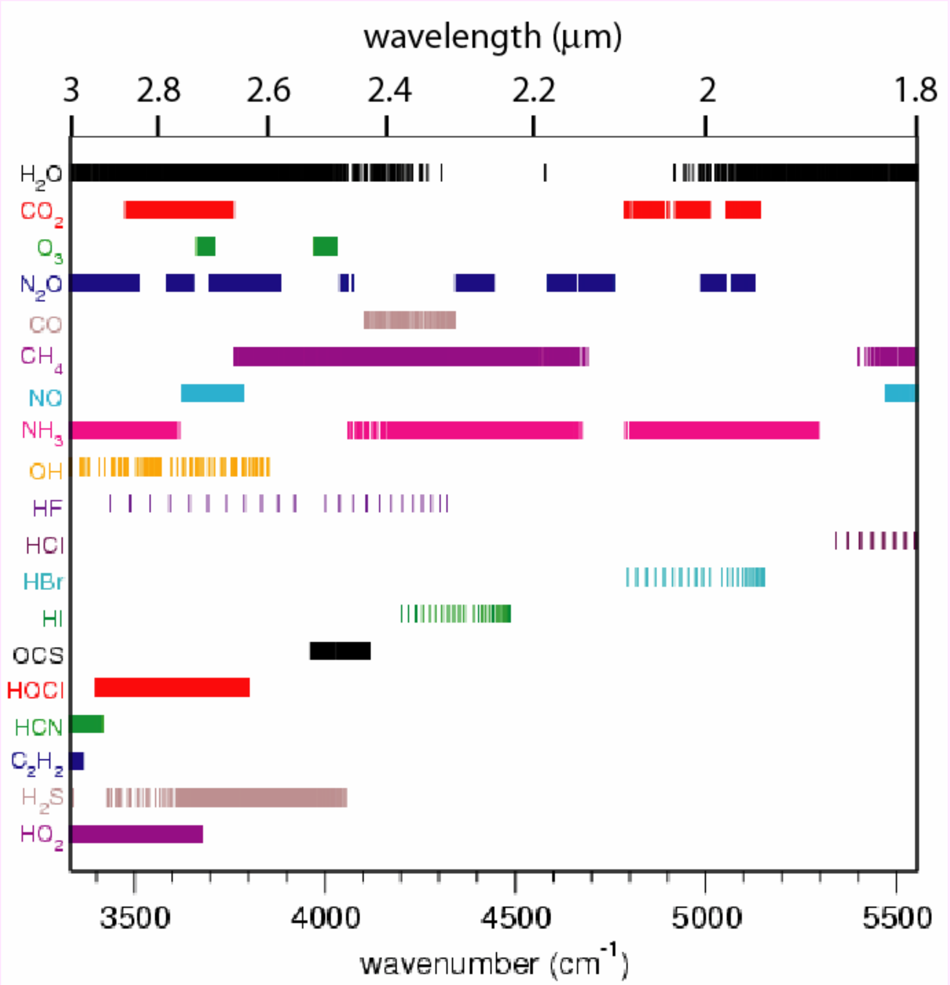
5W ‘TracER’ 532nm
2s exposure

Courtesy of Adam Drysdale / Finlay Colville, Coherent, Inc.

Spectroscopy & Remote Sensing

- 2-3μm: atmospheric transmission
- Good detectors; no practical lasers
- 'Molecular fingerprint' region





Opportunity:

- new, compact, efficient remote sensing systems
- atmospheric, gas pipe-line, pollution monitoring and bio-medical diagnostics

Pumping other lasers

- Multi-Watt circular TEM_{00} beams
- Adjustable wavelength to match solid-state laser absorption
- Optical-to-optical conversion efficiencies >40%

Huber Group, Univ. Hamburg
Blue-green semiconductor disk laser pumped frequency-doubled Pr:YLF
All-solid-state UV (320nm)

Institute of Photonics, University of Strathclyde
2μm Semiconductor disk laser pumped Cr:ZnSe
271mW at ~2.5μm

Conclusions

- Engineeriable:
  - Can design for a particular wavelength
  - 330nm (UV) to 2500nm (mid-IR) (some gaps)
- High Performance
  - >1W possible over this range
  - 40W at 1μm
  - Good beam quality
- Flexible
  - Modelocked (500fs)
  - Single frequency (kHz)
  - Tunable (10s of nm)

BUT:
- Requires good thermal management
- Low energy Q-switched pulses
- Low peak power modelocked pulses

Acknowledgements

PhD Students:

Alex Maclean, Rolf Birch, Lynne Morton, Stephanie Giet, Nils Hempler, Antony Smith, Peter Schlosser.

Staff:

David Burns, Martin Dawson, Stephane Calvez, Jennifer Hastie, John-Mark Hopkins, Patsy Millar, Hannah Foreman.

Sponsors/Collaborators:

EPSRC, EU, DTI, Royal Society of Edinburgh, Royal Academy of Engineering, BAE/Selex, Samsung, Osram, Cablefree, University of Sheffield, Tampere University of Technology, NRC Canada, IAF Freiburg, Ferranti, Sira, Starpoint, Coherent, Toptica, Scottish Enterprise, Thales, Optocap.

And finally…

- **More information on the Institute, our work, PhD/EngD places:**

  Website: www.photonics.ac.uk
  My email: alan.kemp@strath.ac.uk

- **Further reading:**
  - Kemp et al.
    "Semiconductor disk lasers: the future's bright; the colour's flexible"
    The Laser User, Issue 47, p.34, 2007
  - Tropper et al.
    "Vertical-External-Cavity Semiconductor Lasers"
    Journal of Physics D: Applied Physics, 39(9)R74, 2004
  - Hopkins et al.
    "High Power Vertical-External-Cavity Surface-Emitting Lasers"
    Physics Status Solidi (c), 3(3)380, 2006