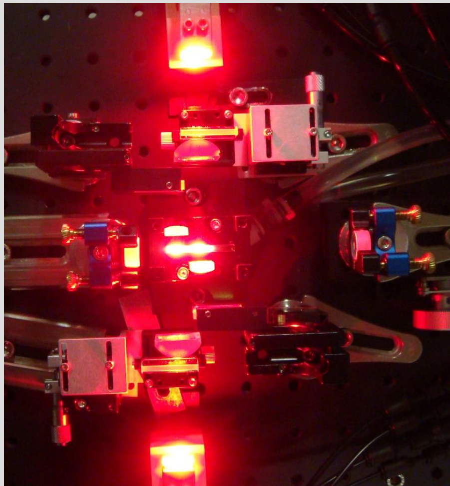
Imperial College London

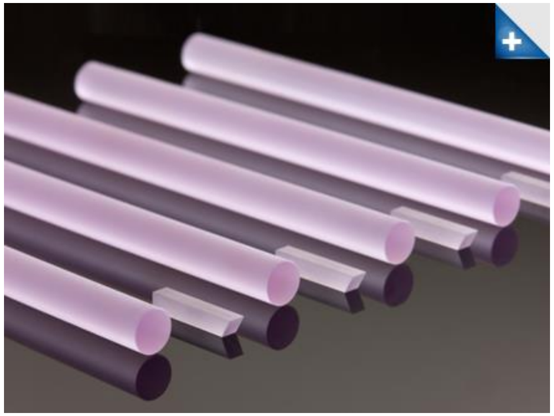
Siegman International School on Lasers
August 2017, CIO Mexico

Space Lasers 2

Professor Mike Damzen
Imperial College London, UK



Alexandrite as an alternative to Nd:YAG?



Nd:YAG

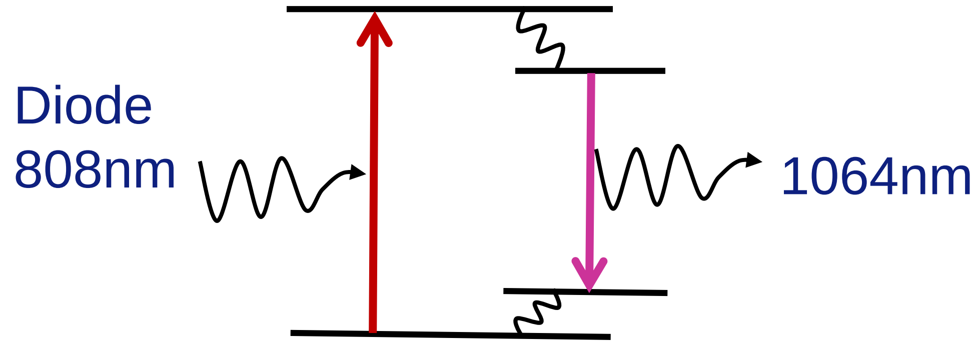
$Nd^{3+}:Y_3Al_5O_{12}$

Alexandrite

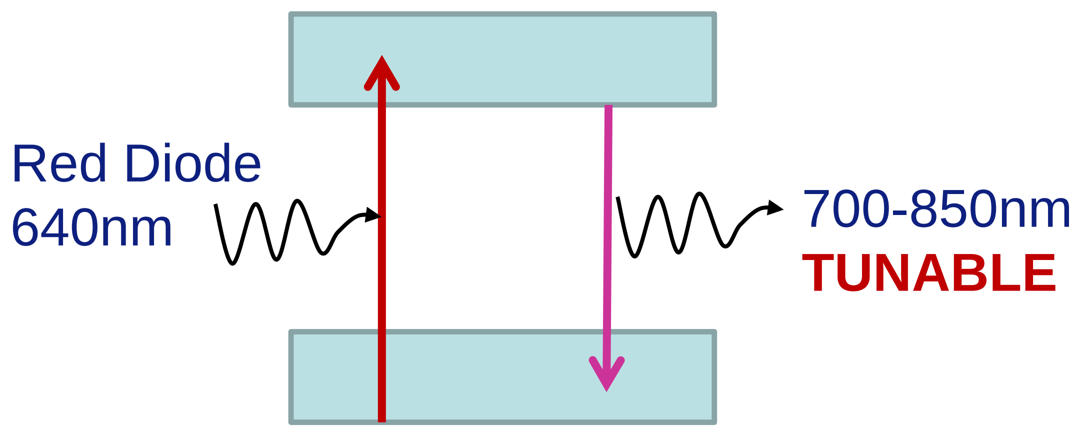
Cr-doped Chrysoberyl

$Cr^{3+}:BeAl_2O_4$

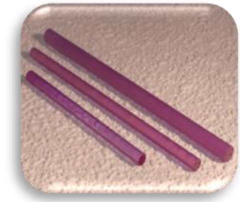
Nd:YAG



Alexandrite



Why Alexandrite?



Tunable (λ)
~700-850nm

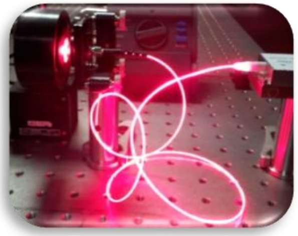
High Power (P)
~100W

High Energy (E)
>1J

Lamp-Pumped

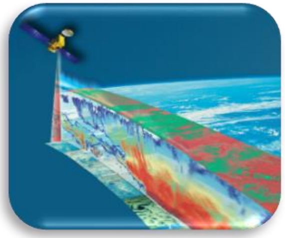
Cosmetic medical market

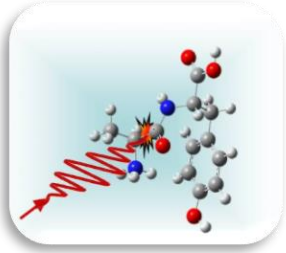
Diode-Pumped



High efficiency
compact
long lifetime

Enable new applications





Remote Sensing provides valuable data

Diode-pumped Alexandrite

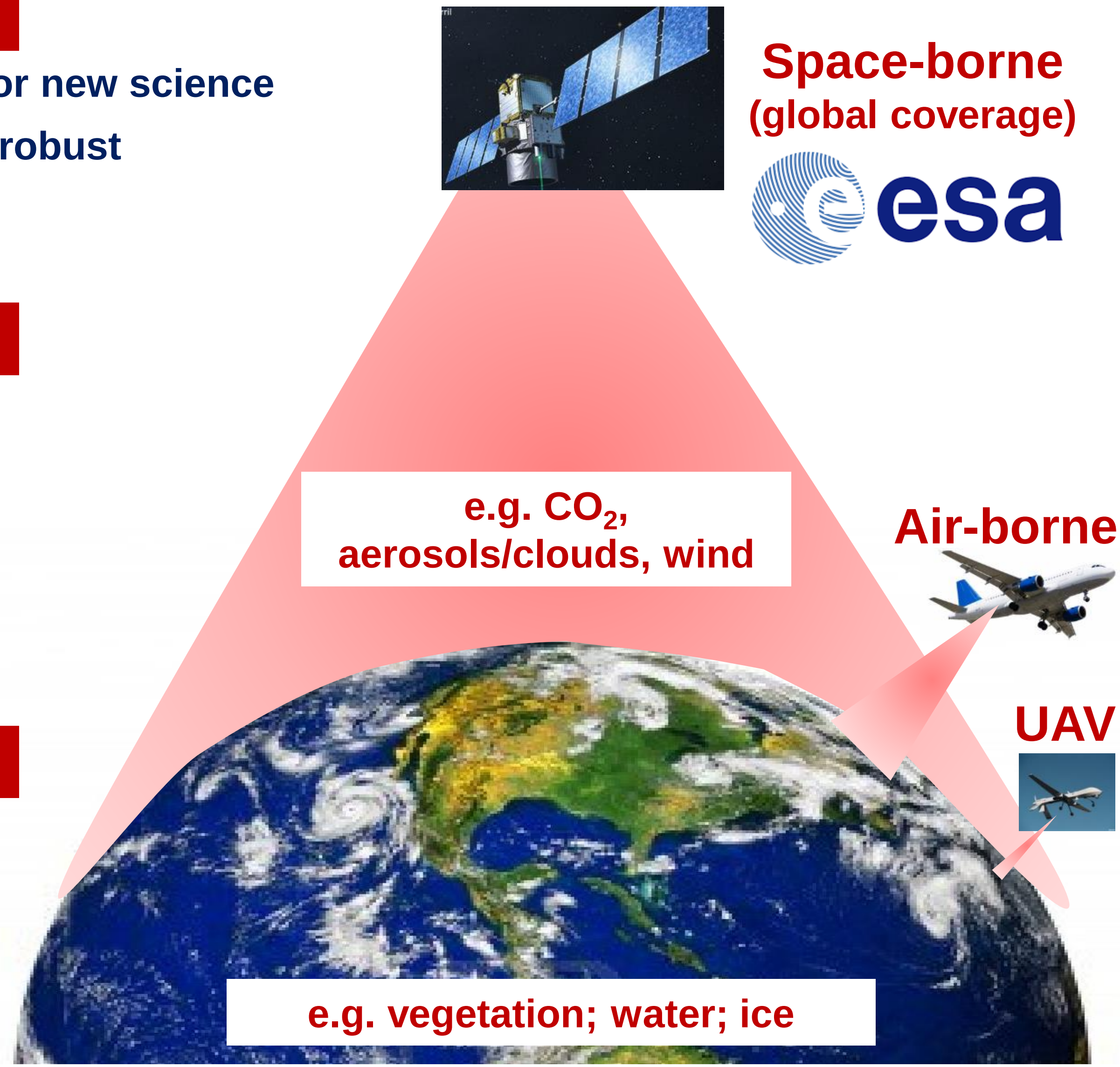
- New waveband & tunability for new science
- High efficiency (NIR & UV) & robust

Atmospheric monitoring:

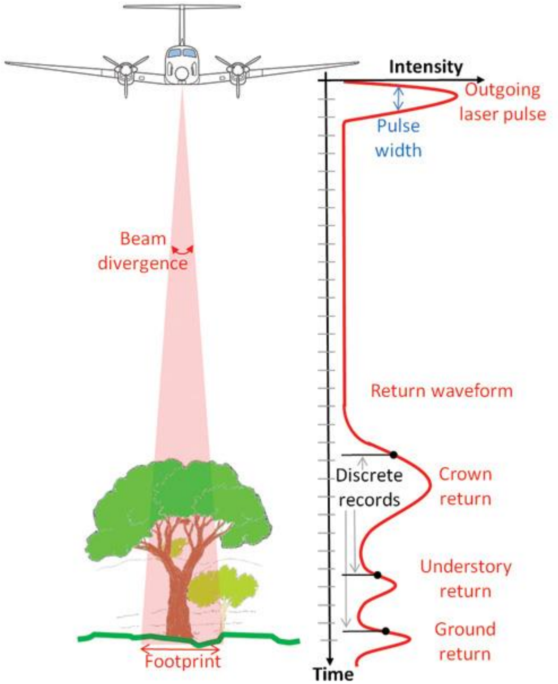
- Climate change science
- Atmospheric science
- Weather prediction

Earth System monitoring:

- Health of Earth's bio-sphere
- Crop / Forestry management
- Disaster management

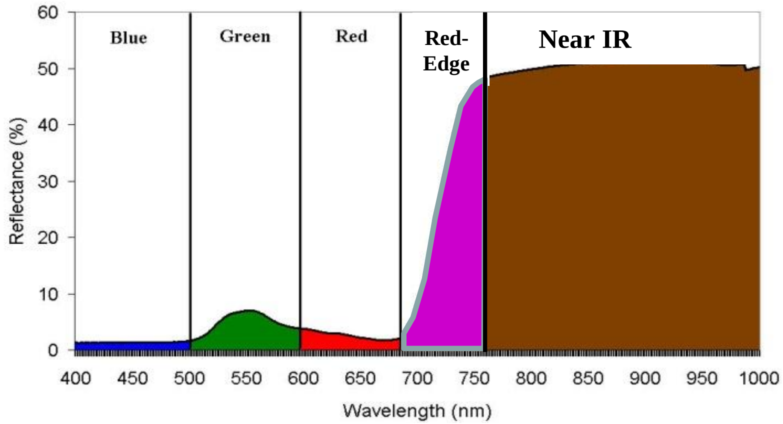


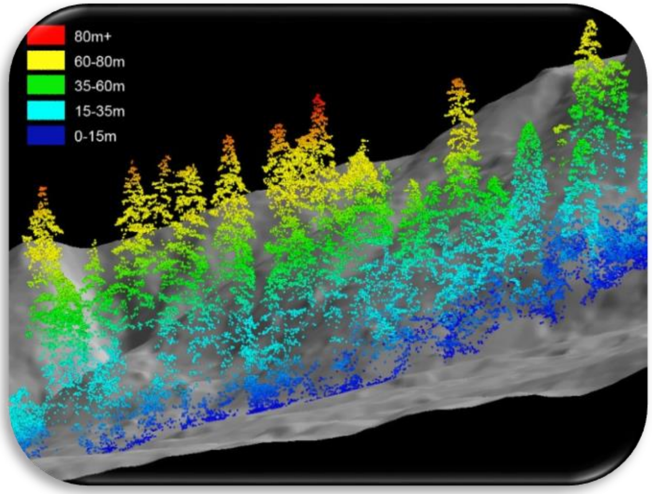
Alexandrite for Vegetation Lidar



“...see the woods and the trees!”

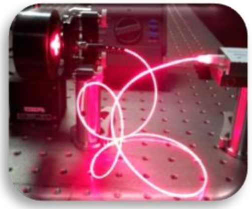
Alexandrite operates across the red-edge band of vegetation





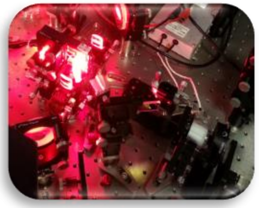
Outline

- **Introduction to Alexandrite**
- **Diode-Pumped Alexandrite**
    - ➢ *Fundamental Studies (>1W, TEM_{00})*



    - ➢ *Power Scaling Results (multi-10W)*

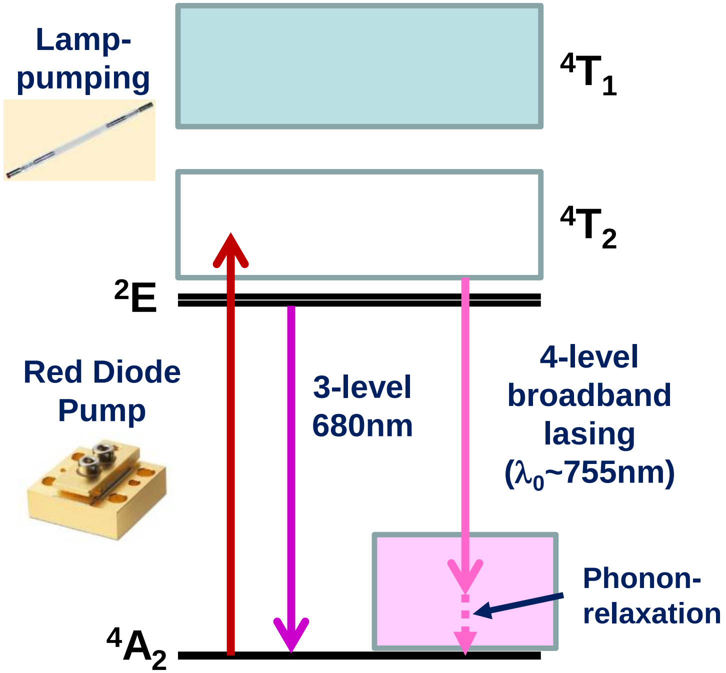
    - ➢ *Systems Development (Q-switched)*



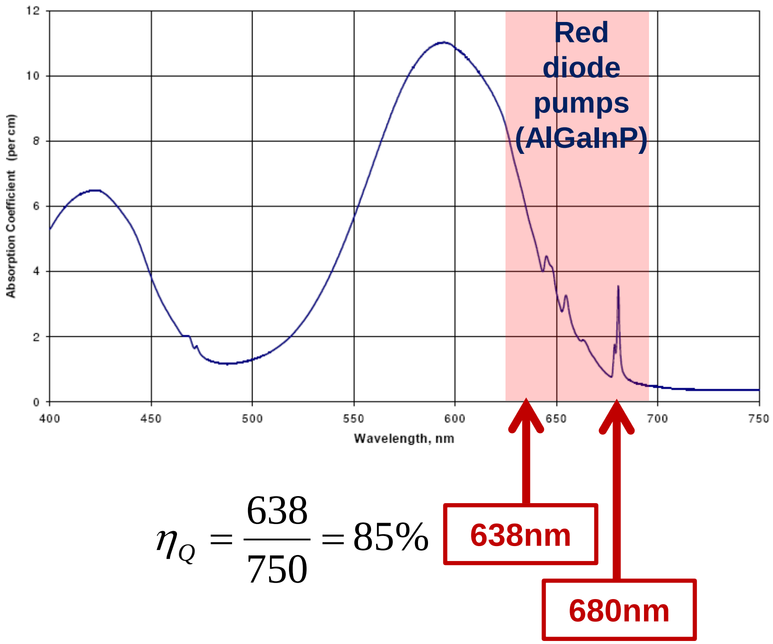
- **Conclusions**

What is Alexandrite?

- Alexandrite = Cr^{3+}-doped Chrysoberyl ($Cr^{3+}:BeAl_2O_4$)
- First room-temperature vibronic laser (1978)
- Broad absorption (pump) bands across visible
- 3-level lasing transition (^2E – $^4A_2$) @ 680nm (R-line)
- Broadband 4-level lasing ($^4T_2$ – $^4A_2$) centred @ ~ 755nm



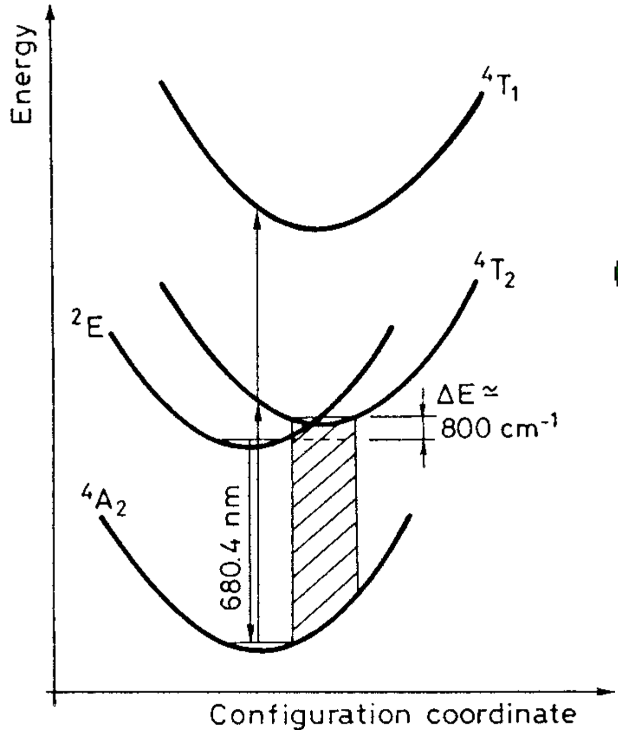
Alexandrite
($Cr^{3+}:BeAl_2O_4$)

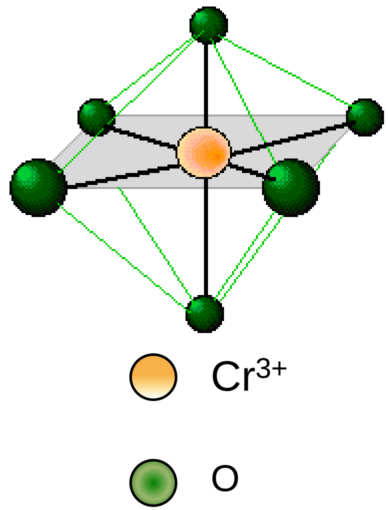


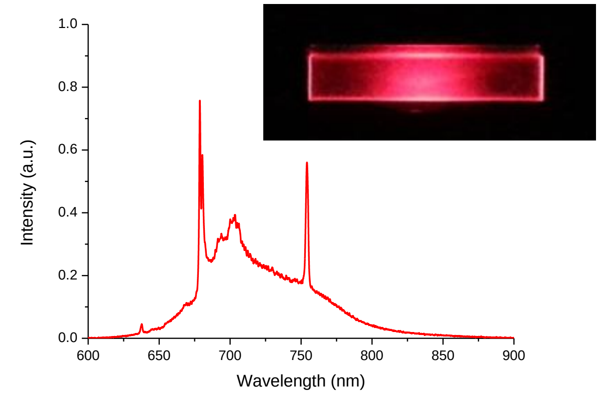
$$\eta_Q = \frac{638}{750} = 85\%$$

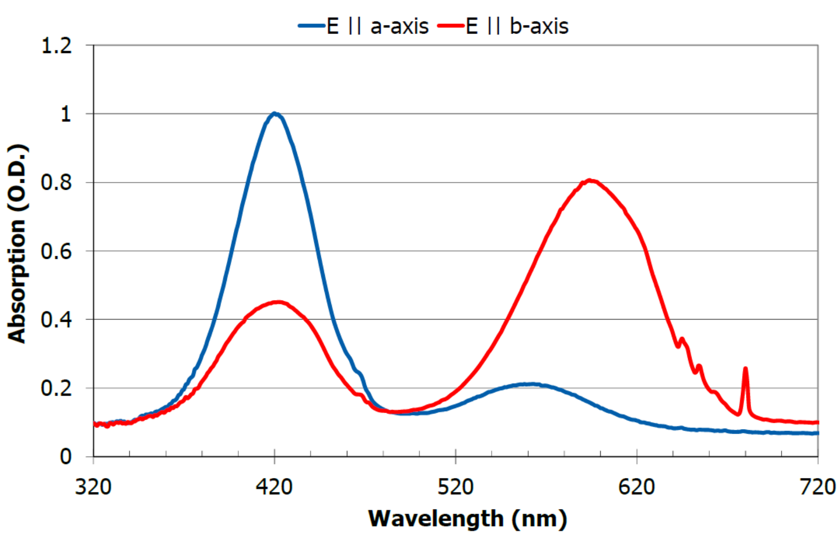
$$\eta_Q = \frac{680}{750} = 91\%$$

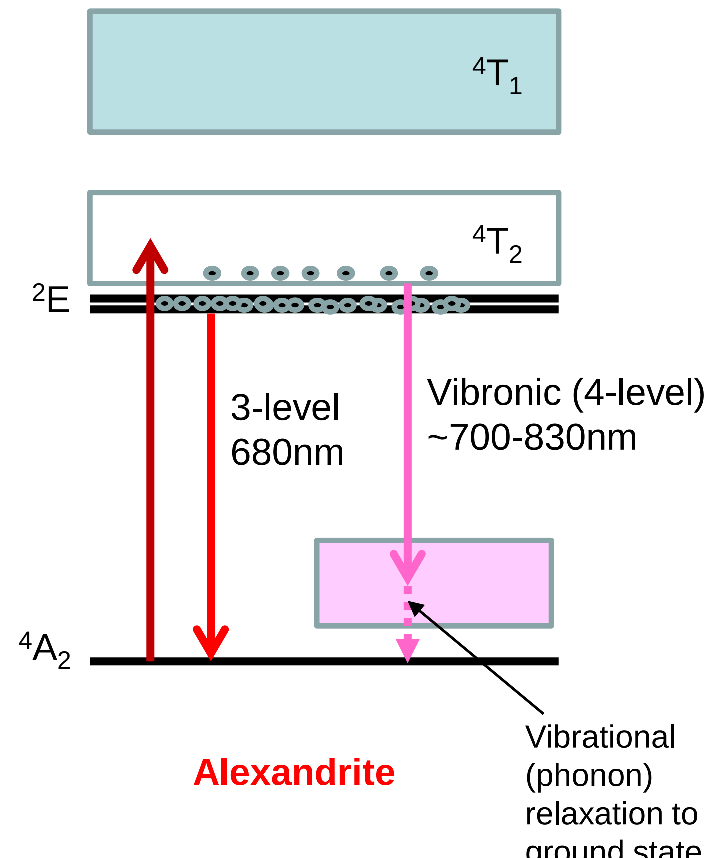
Alexandrite Lasing Spectroscopy



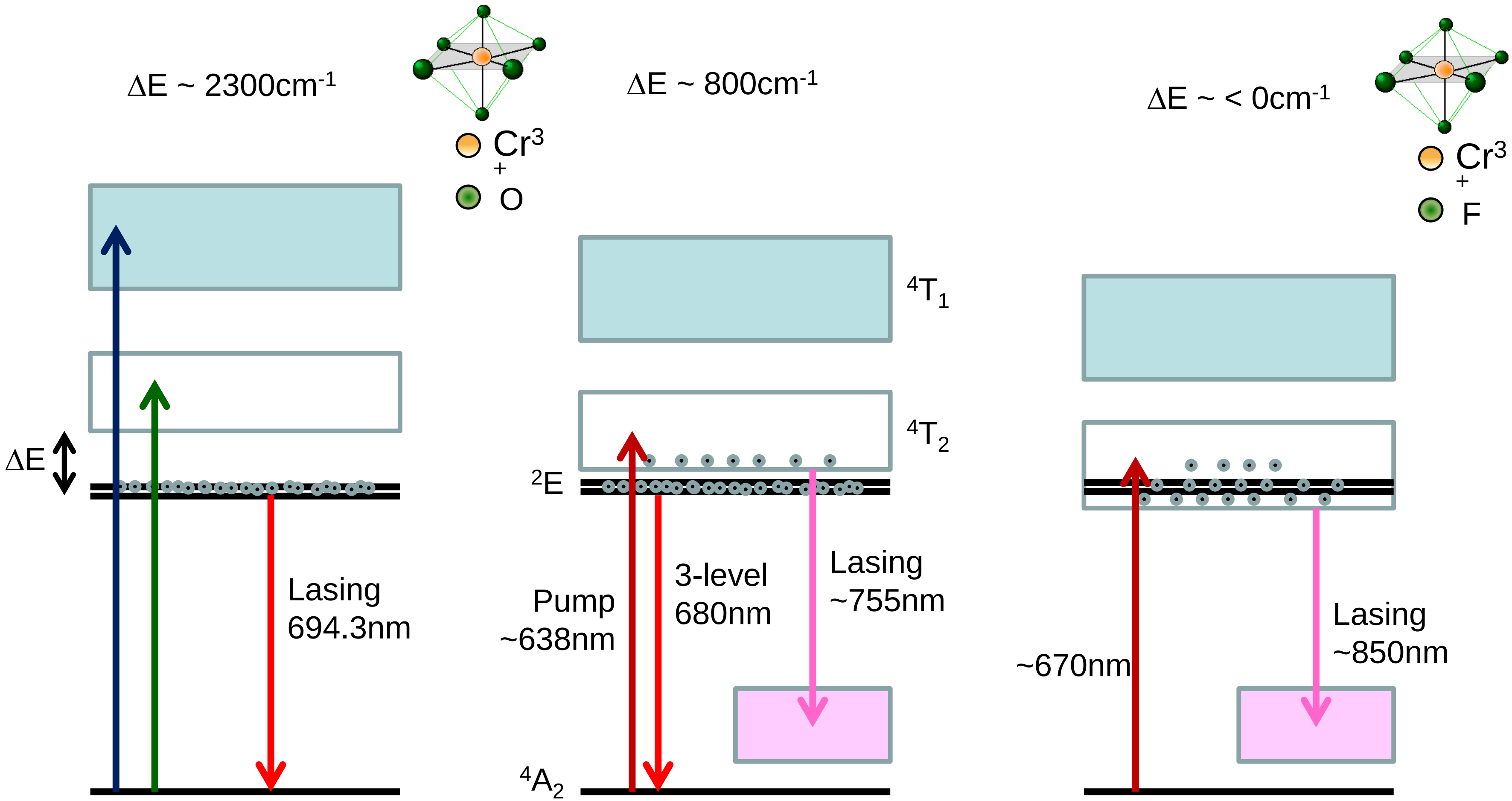








Comparison of Cr-doped lasers



Ruby	**Alexandrite**	**Cr:LiSAF**
Unpopulated vibronic states. Only 3-level lasing from ^2E state.	Populated (few %) vibronic states. Vibronic lasing from $^4T_2$ state. (3-level lasing also possible)	More highly populated vibronic states. Vibronic lasing from $^4T_2$ state.
Cr^{3+}:Al_2O_3	**Cr^{3+}:$BeAl_2O_4$**	**Cr^{3+}:$LiSrAlF_3$**

Alexandrite - an excellent material for high pulse power

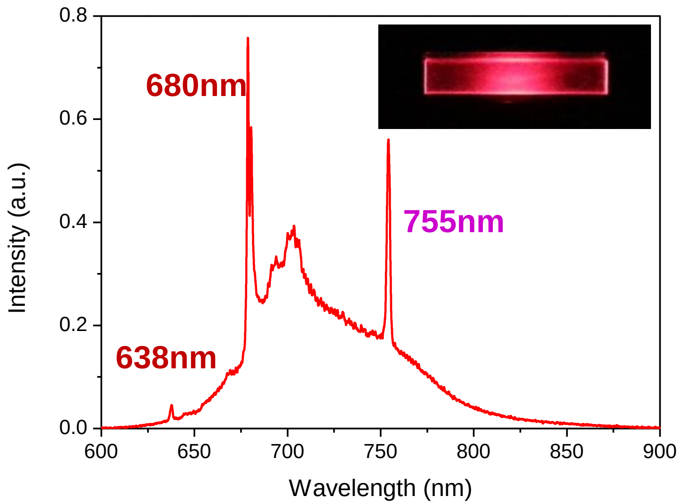
- **Broad tunability (~700-850nm)**
- **High thermal conductivity 23 $Wm^{-1}K^{-1}$ (x2 Nd:YAG)**
- **High fracture resistance (x5 Nd:YAG)**
- **Linearly-polarised (no depolarisation issues)**
- **High laser-induced damage threshold (>270J/cm^2)**
- **Long storage time 260μs (Ti:S - 3μs)** → *Diode-pumped Q-switching*

High Power

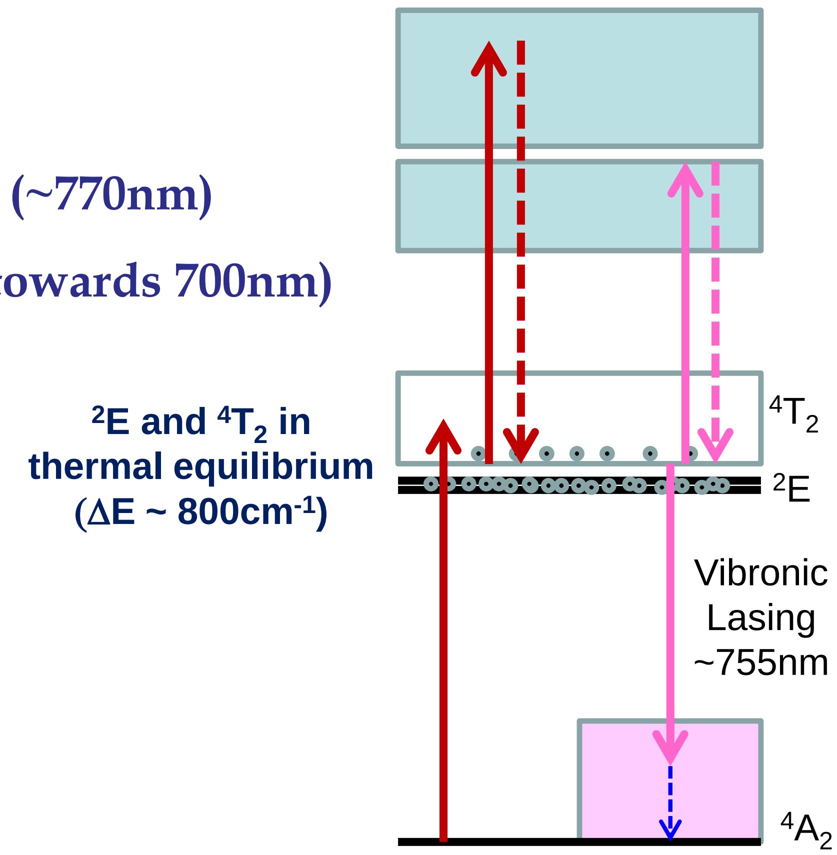
Alexandrite	**Tuning Range**	
Fundamental	**700 – 850 nm**	**NIR**
SHG	**350 – 425 nm**	**UV / Blue**
THG	**233 – 287 nm**	**Deep UV**
FHG	**175 – 212 nm**	

Alexandrite is a complicated lasing system

- Low stimulated emission cross-section σ_e *(0.7 10^{-20} cm^2)*
- Effective σ_e increases with T (larger Boltzmann filling factor)
- Upper-state lifetime (τ) decreases with T
- ESA is present $\sigma_2(\lambda)$
    - at laser and pump wavelengths
    - minimum in centre of lasing band (~770nm)
- GSA (most important at short lasing λ towards 700nm)



Fluorescent emission of Alexandrite



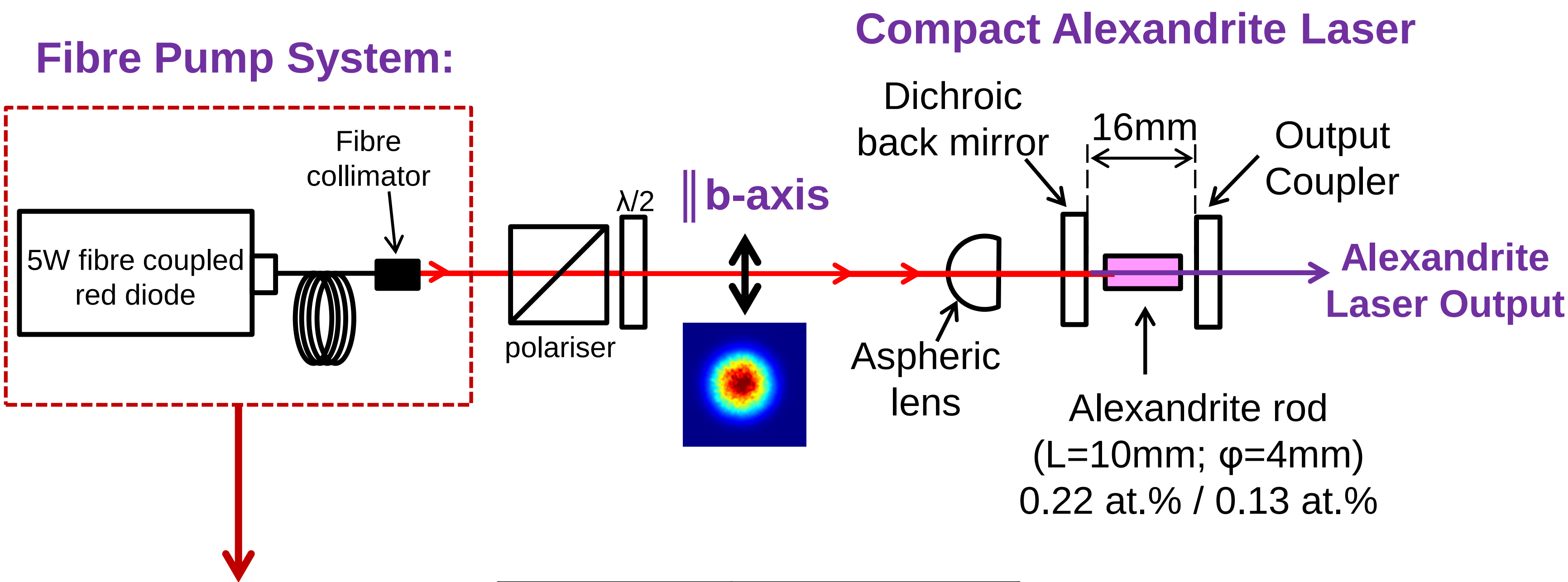
Alexandrite

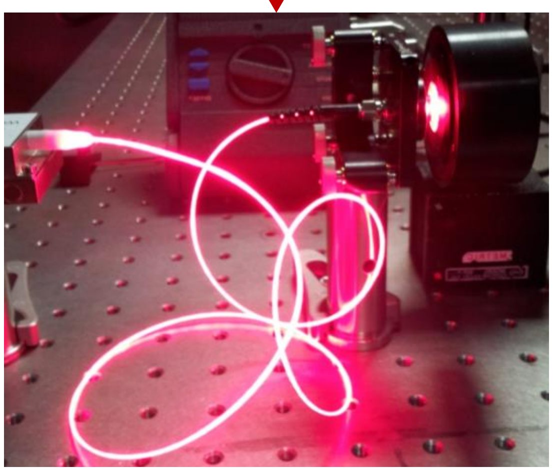
Prior Diode-Pumped Alexandrite?

Year	Author	Power	Slope eff.
1990	Scheps	2mW	25%
1993	Scheps	25mW	28%
2005	Peng	1.3W	24%
2013 2014	Beyatli Yorulmaz	195mW 48mW	34% 36%

Fibre-delivered diode-pumped Alexandrite

Fibre-coupled Red-Diode-Pumped Alexandrite Laser

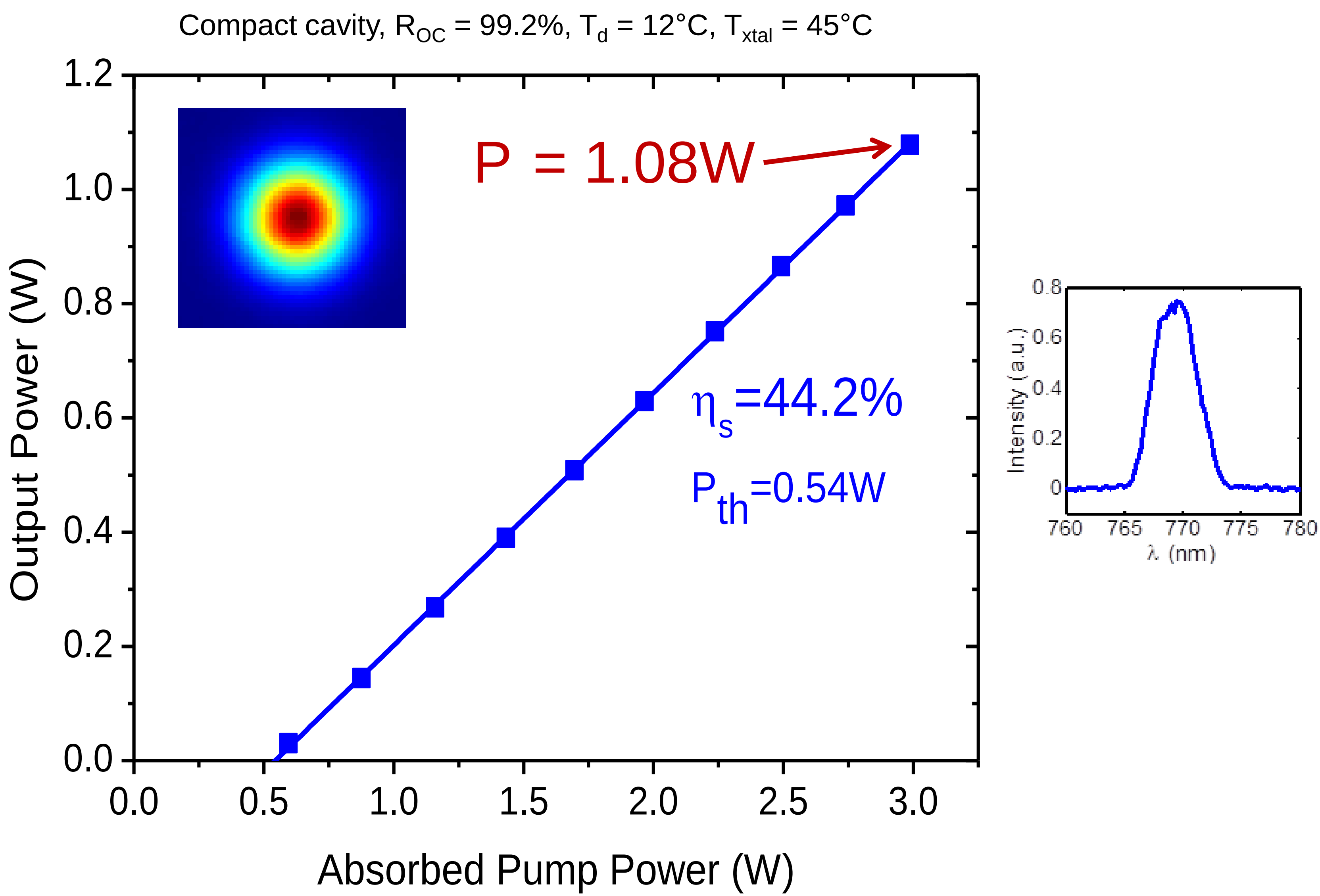




Parameter	(nominal) Value
Power	5 W
Wavelength	636 nm
Spatial (M^2)	43
Polarisation	unpolarised
Fibre core	105 μm
Fibre NA	0.22

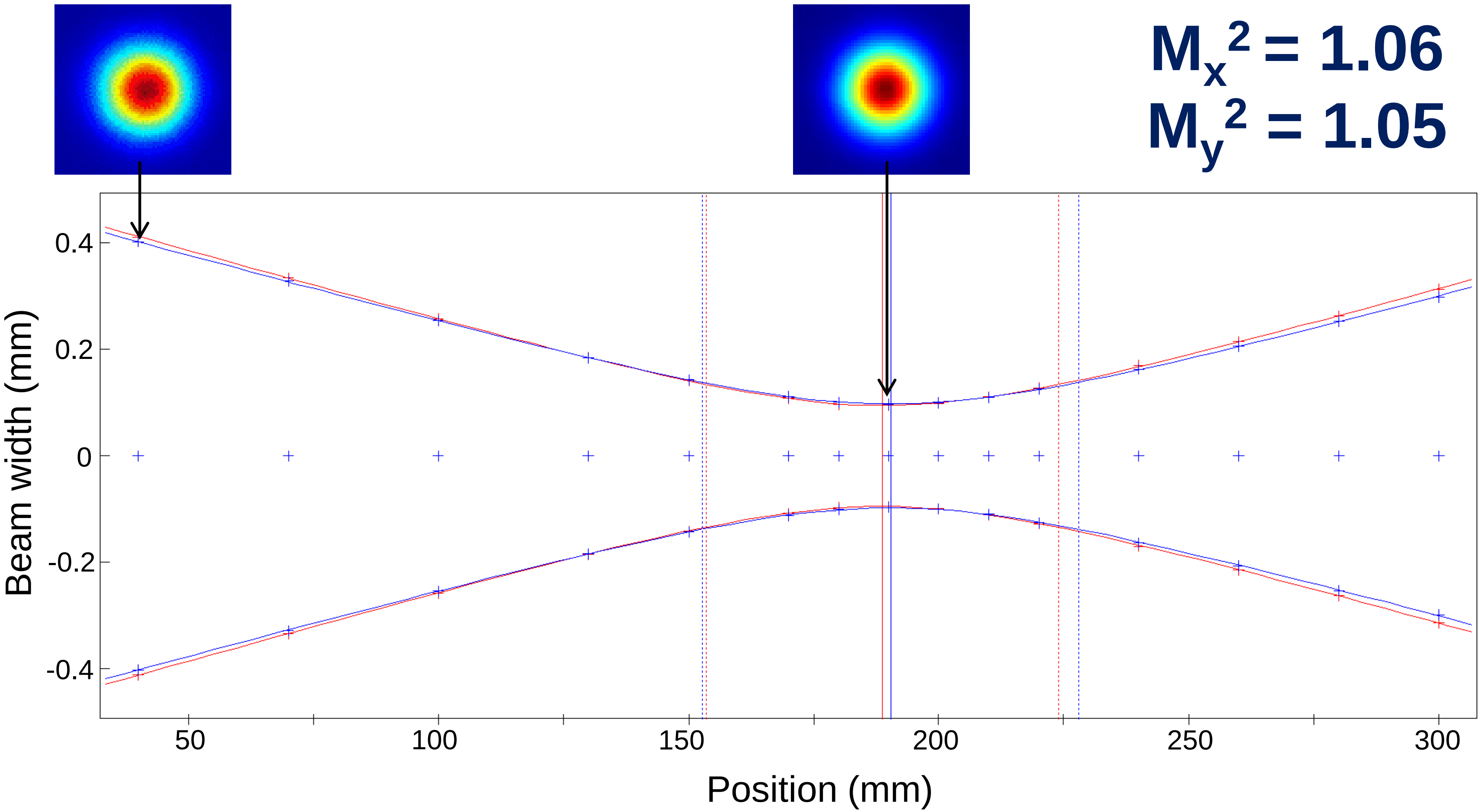
> 1W, TEM_{00} Alexandrite laser

Highest Power 1.08W (& slope efficiency 44.2%) TEM_{00} mode



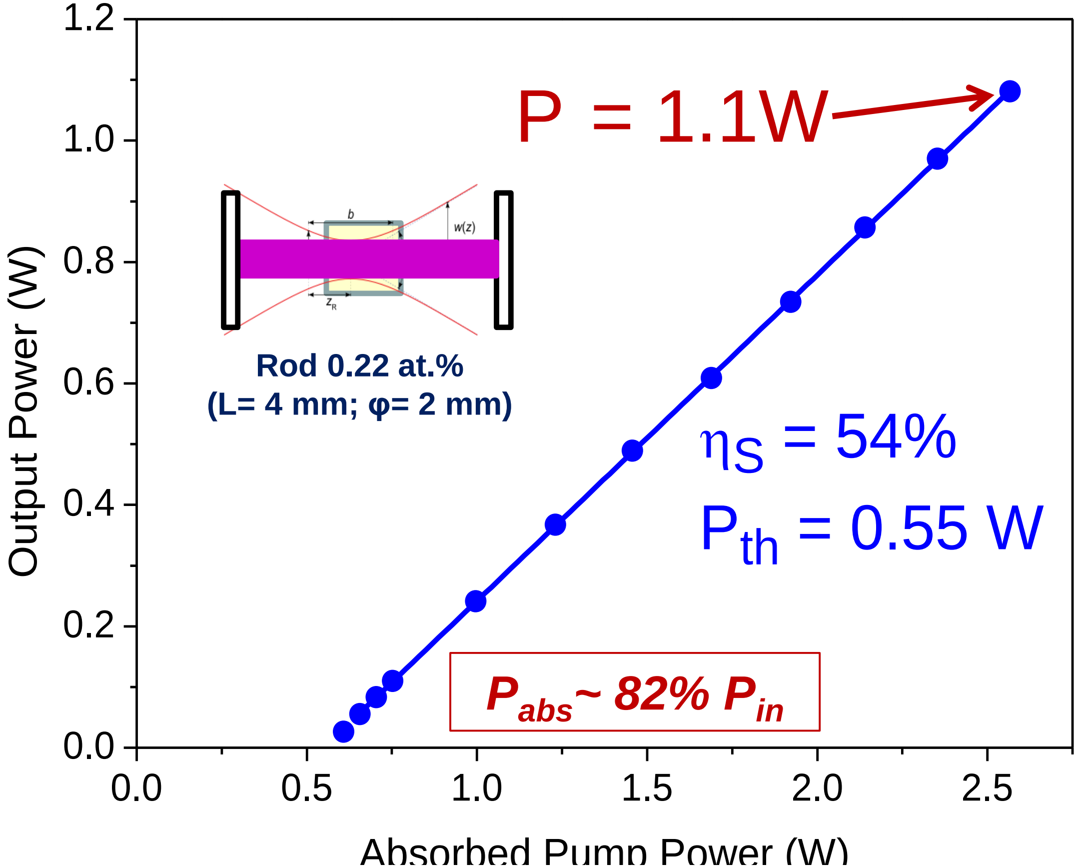
Excellent TEM_{00} Mode Quality

TEM_{00} mode with M^2 ~ 1.05 at maximum power P = 1.08W

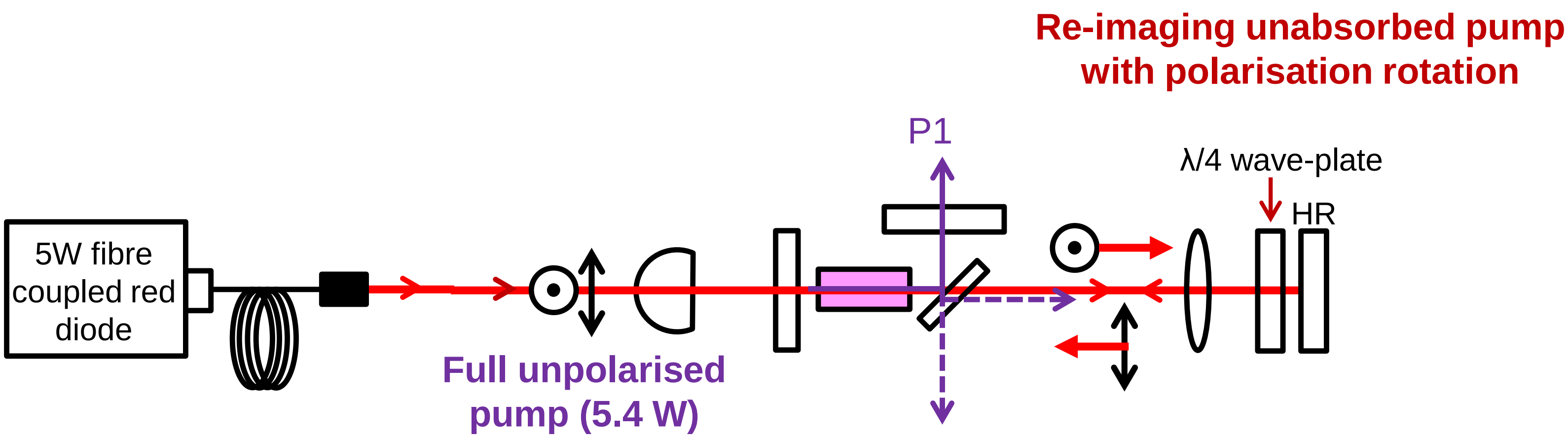


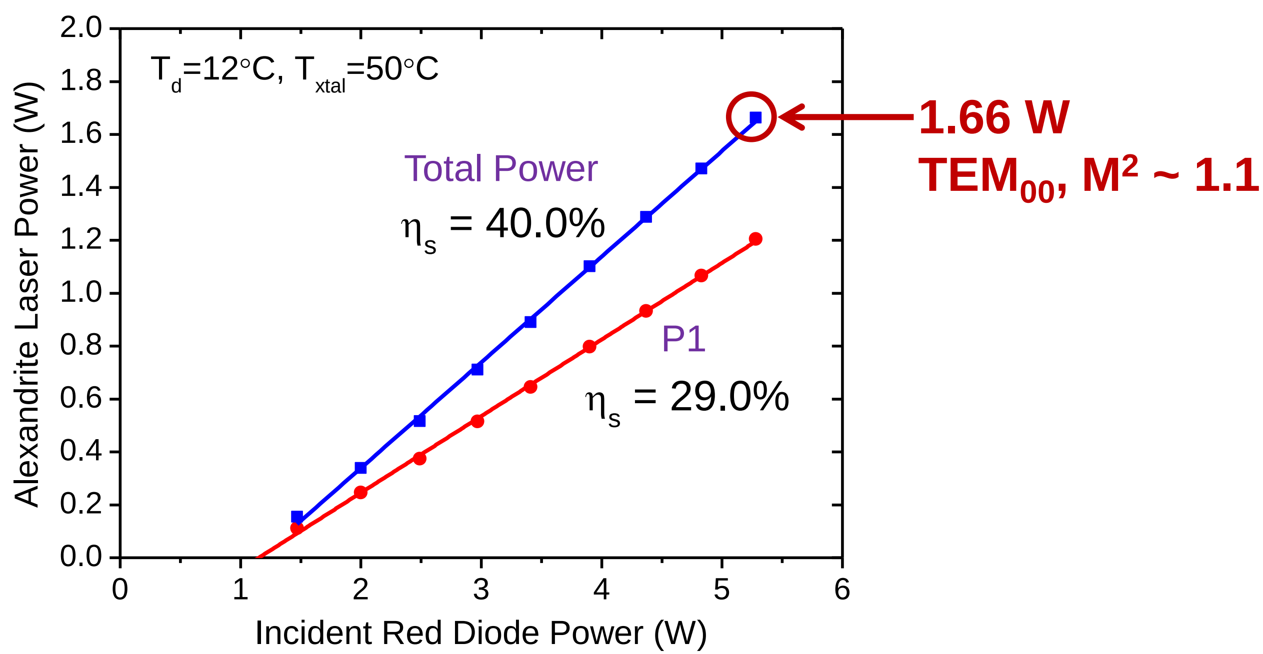
Enhanced Slope Efficiency with short Alexandrite rod (L=4mm)

•TEM_{00} ; M^2 = 1.05



Alexandrite Laser – double-pass pumping





Improving Theoretical Modelling of Alexandrite Laser

> 100 nm tuning range | **Pump ESA measurement**

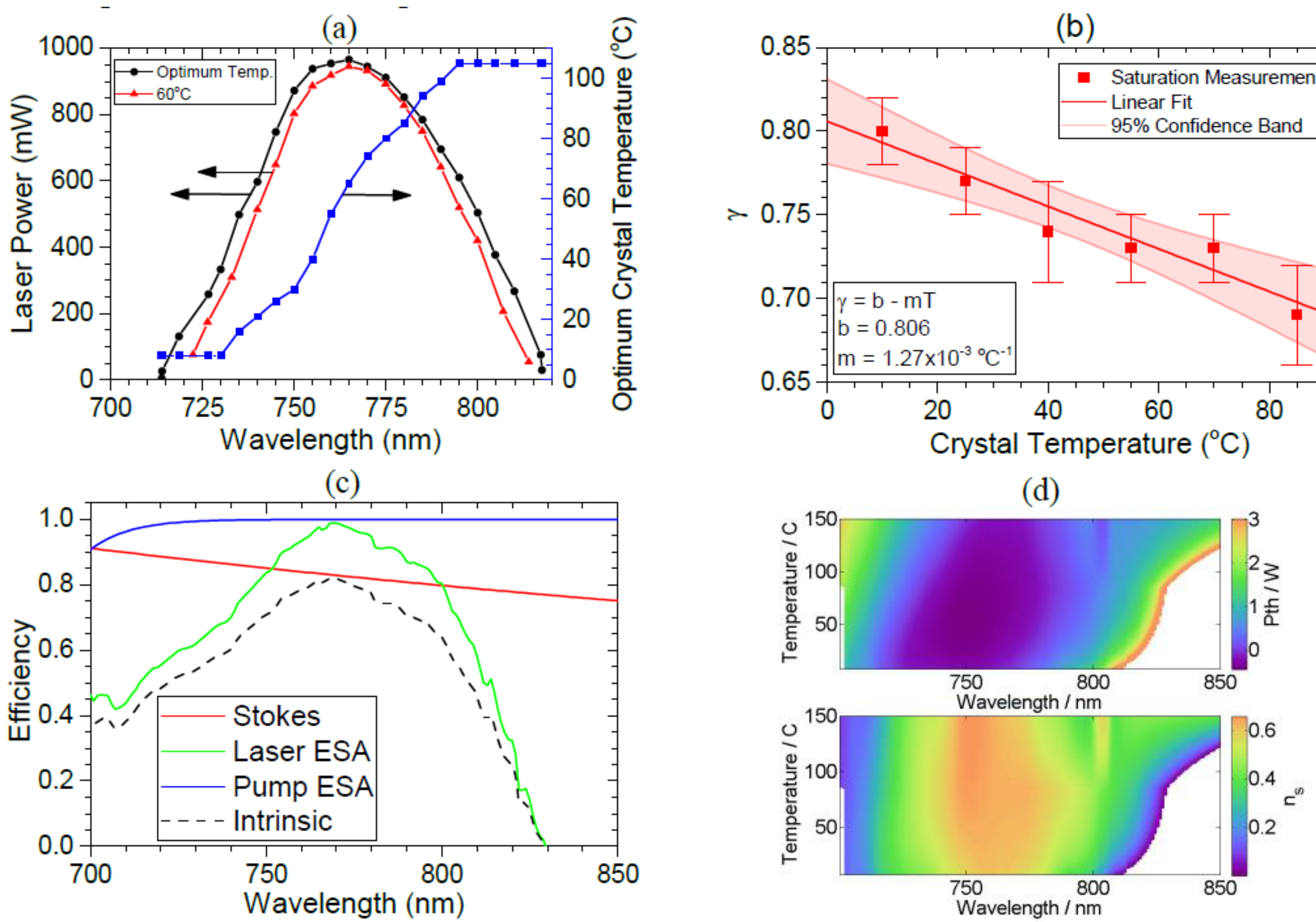
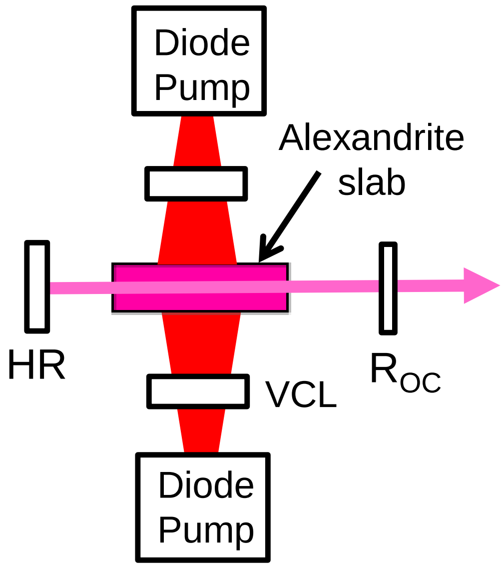


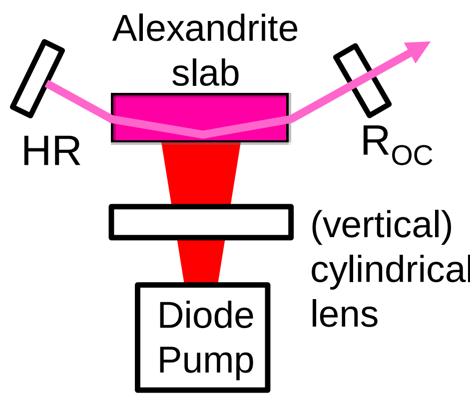
Fig. 1 (a) Laser power against wavelength for a temperature controlled laser. (b) ESA ratio γ against crystal temperature in Alexandrite. (c) Intrinsic efficiency of Alexandrite along with its constituent components. (d) Threshold (top) and slope efficiency (bottom) of an Alexandrite laser versus crystal temperature and wavelength.

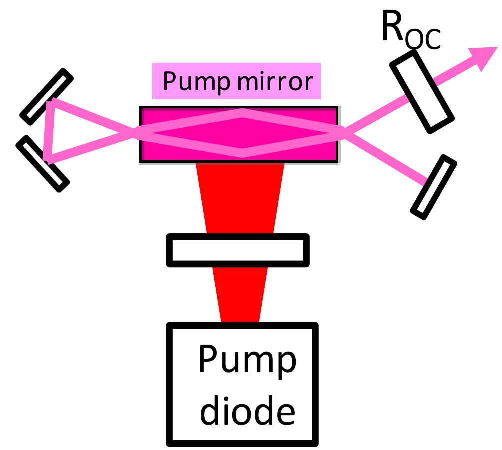
Power-scaling diode-pumped Alexandrite

Diode-pumped Alexandrite – Power scaling strategies

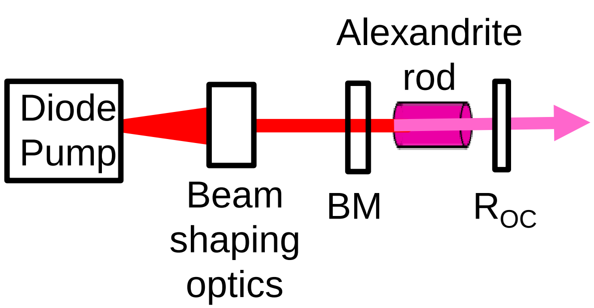
Side-Pumped Slab – strategies for power scalability

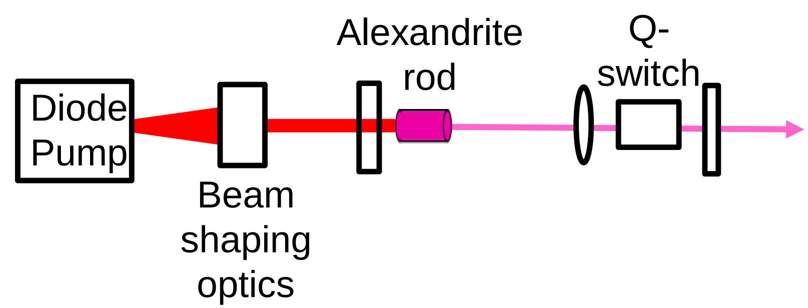






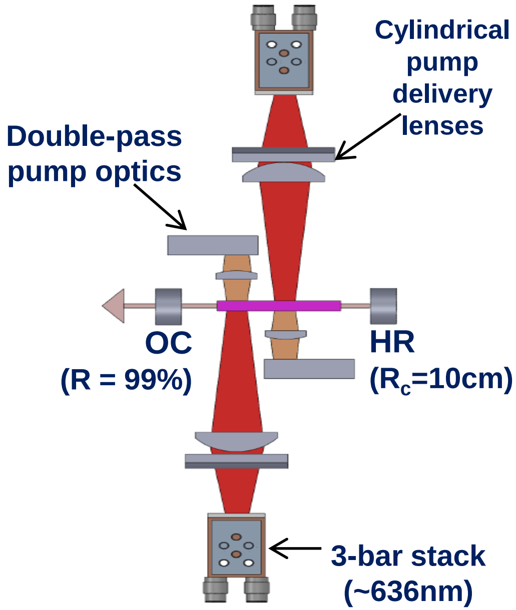
High-power End-Pumped Rod

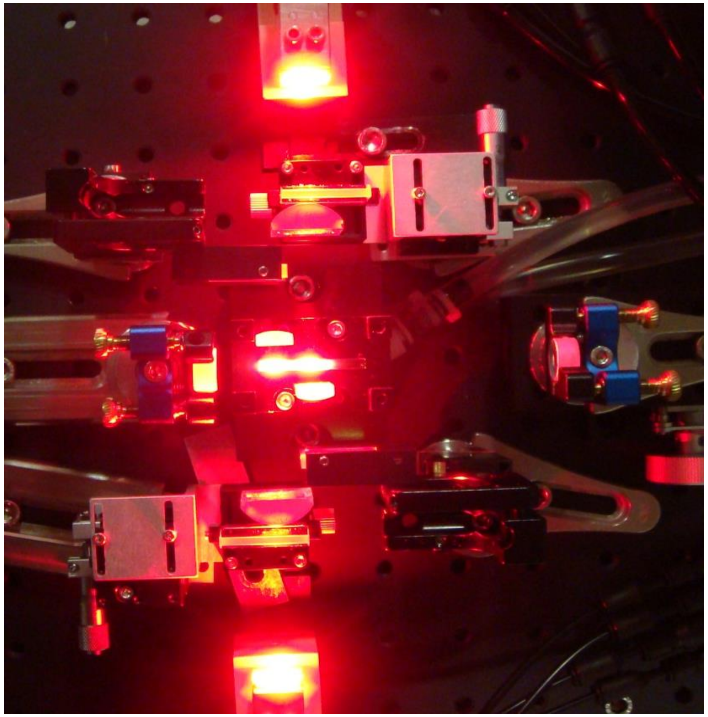




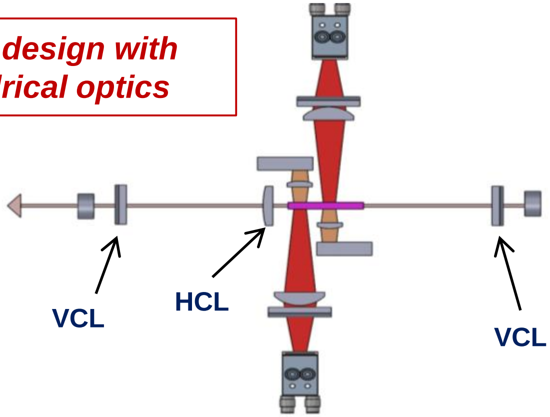
Diode-side-pumped Slab Alexandrite Laser

- Alexandrite slab: 20 x 2 x 2 mm (L x w x h) and doping 0.21 at% Cr.





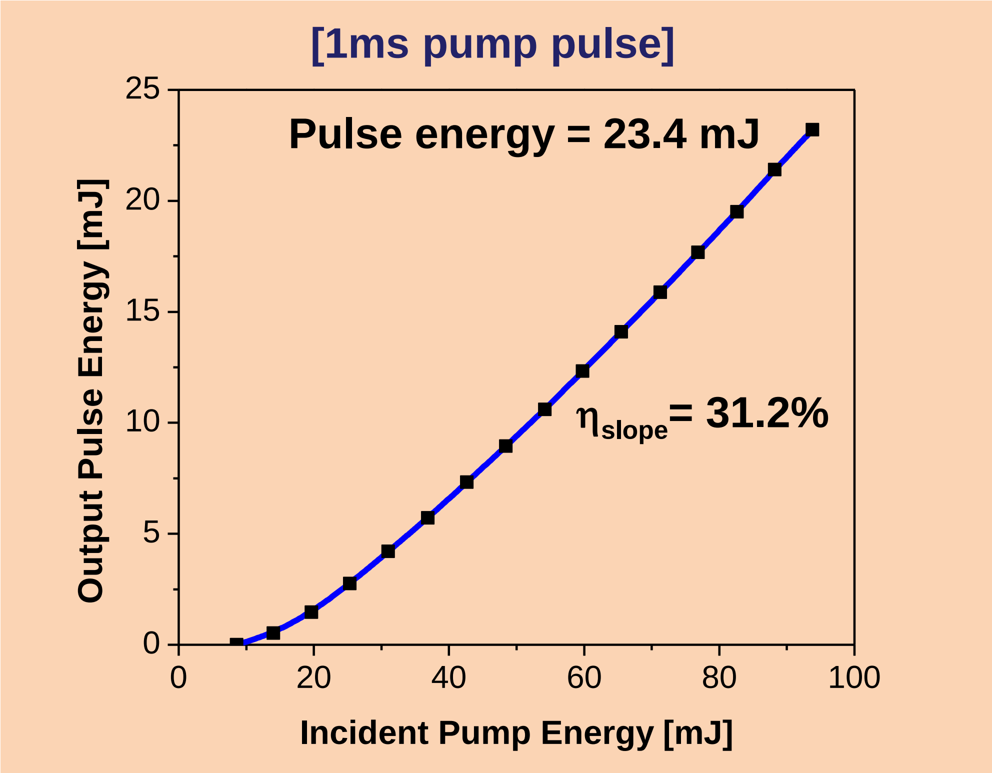
TEM$_{00}$ design with cylindrical optics

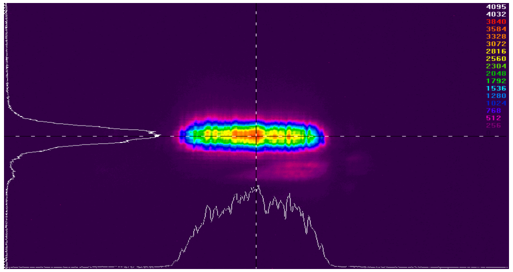


3-bar stack (FAC)~636nm

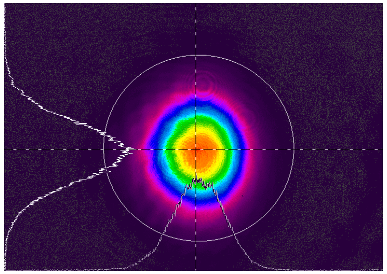
First Multi-Watt Diode-Pumped Alexandrite Laser

- ‘Free-running’ pulse energy 23.4 mJ@100Hz (1ms QCW pump)
- Slope efficiency 42% (wrt absorbed pump)
- Average power 2.34W (6.4 W with CW pumping)





M^2 ~ 10 x 1

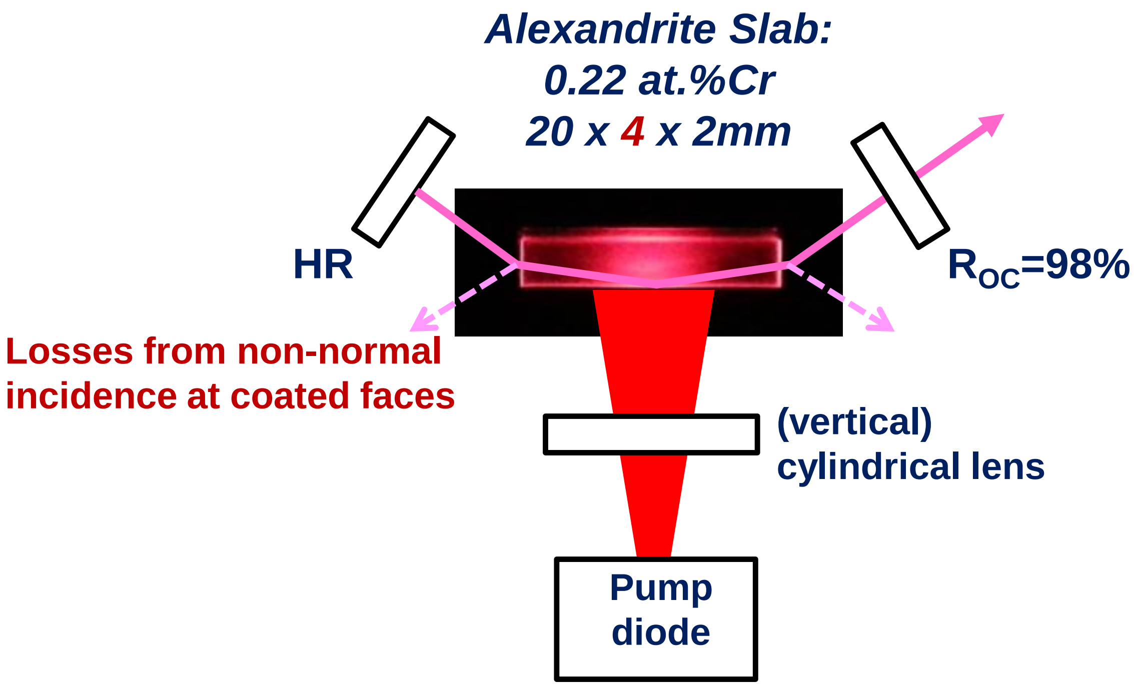


M^2 ~ 1.2

With cylindrical optics but much reduced power

Alexandrite Bounce Laser

Grazing-incidence (θ~9^0) TIR bounce path from the pump face

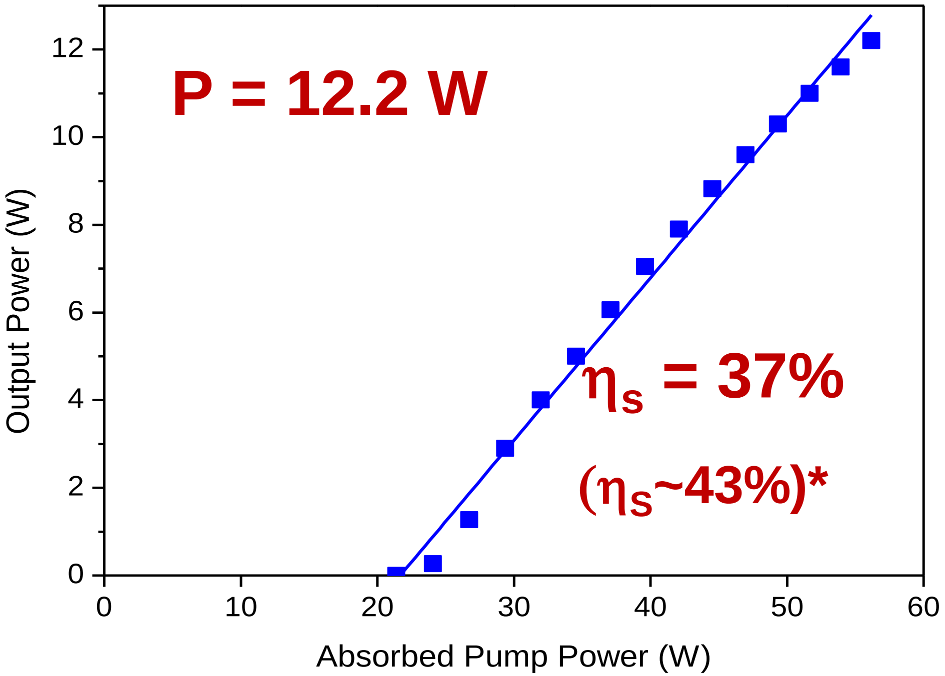


Pump: 60W diode module @ 638nm

Fast axis: M_f^2 ~25
Slow axis: M_s^2 ~250

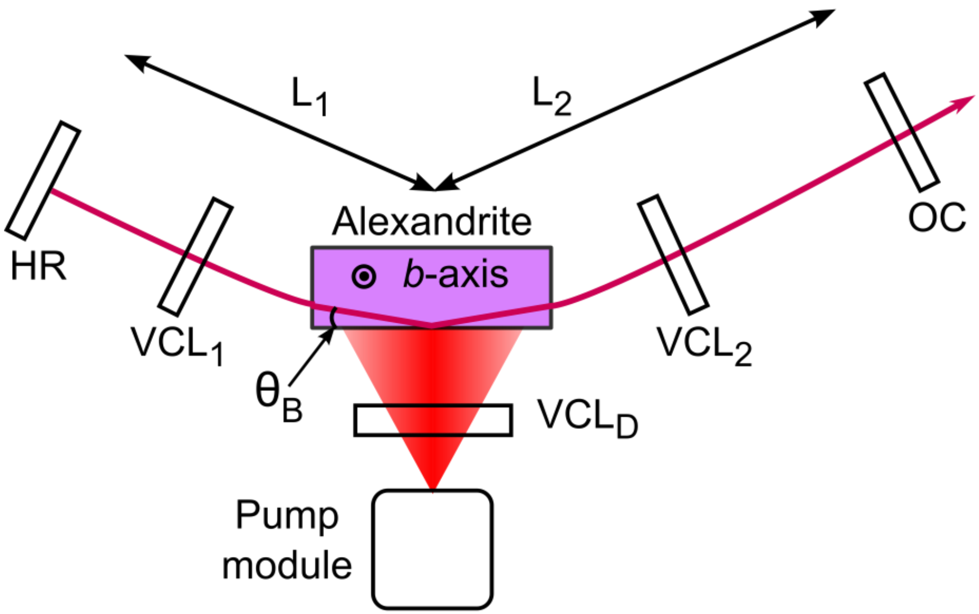
First Alexandrite Bounce Laser (>12W)

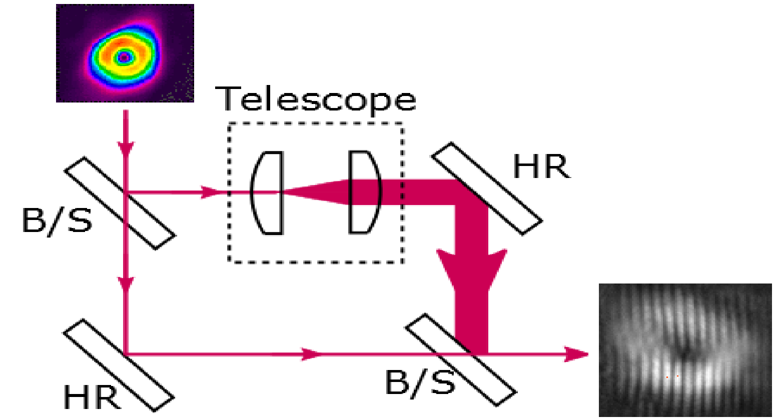
- **Slope efficiency = 37% (43% including slab losses)**
- **Spatial: single mode vertical; multimode horizontal**

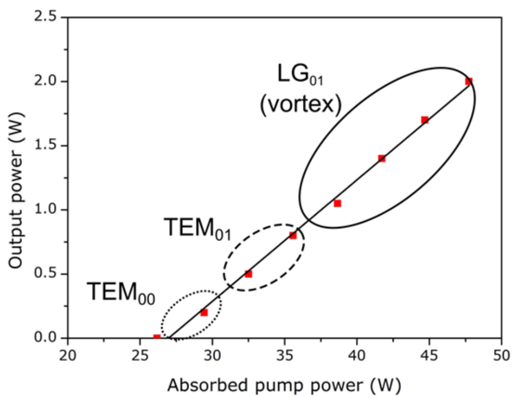


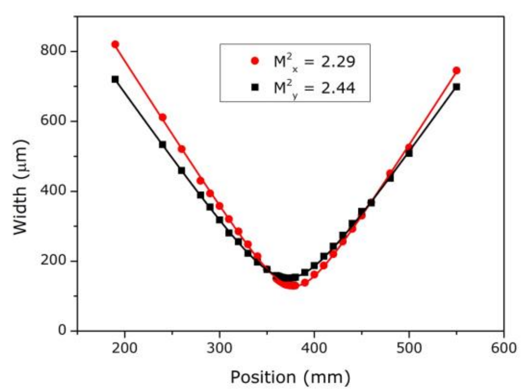
*** >2W reflections from AR-coated slab end faces.**

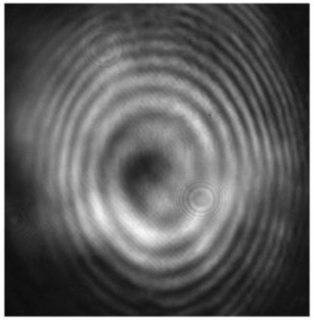
First Direct Vortex Generation from a Vibronic Laser

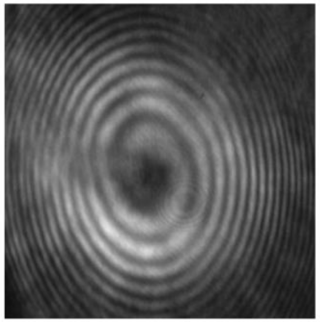






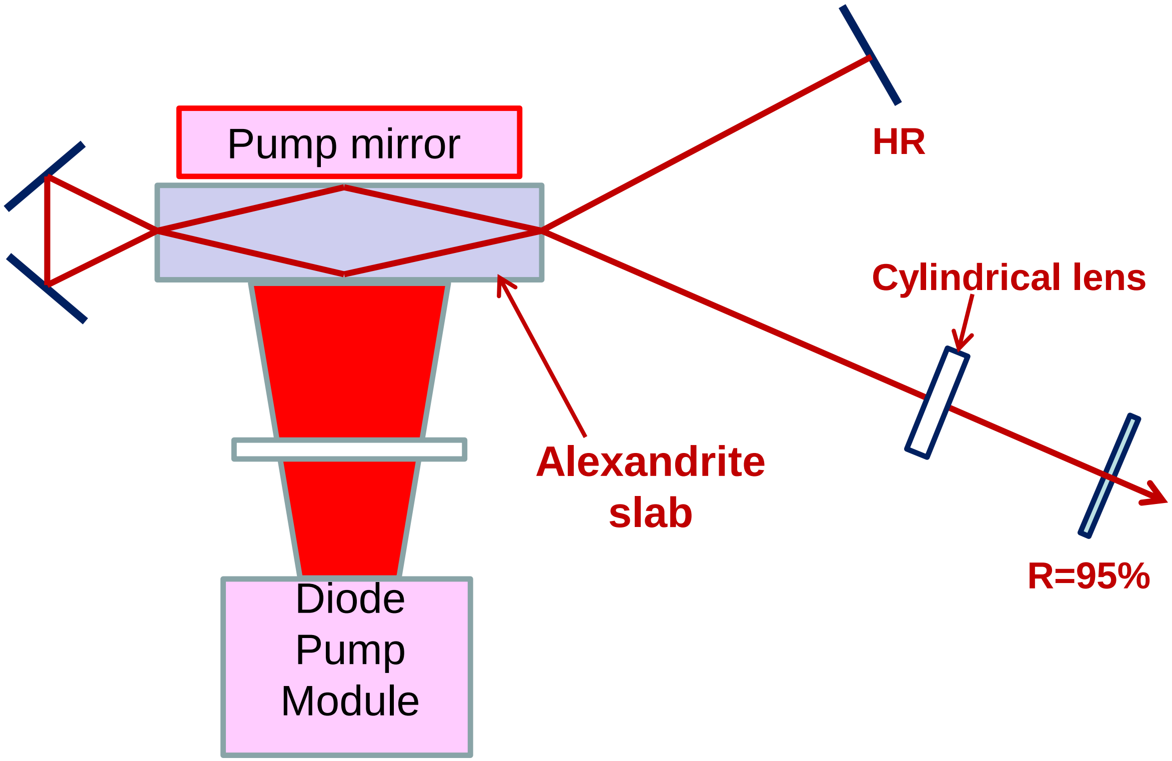






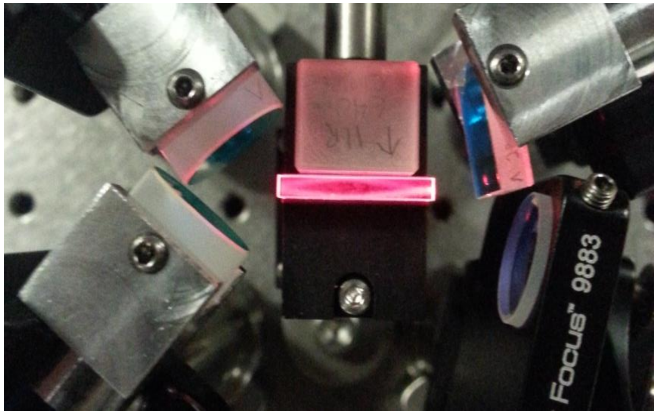
Alexandrite Double-Bounce Laser

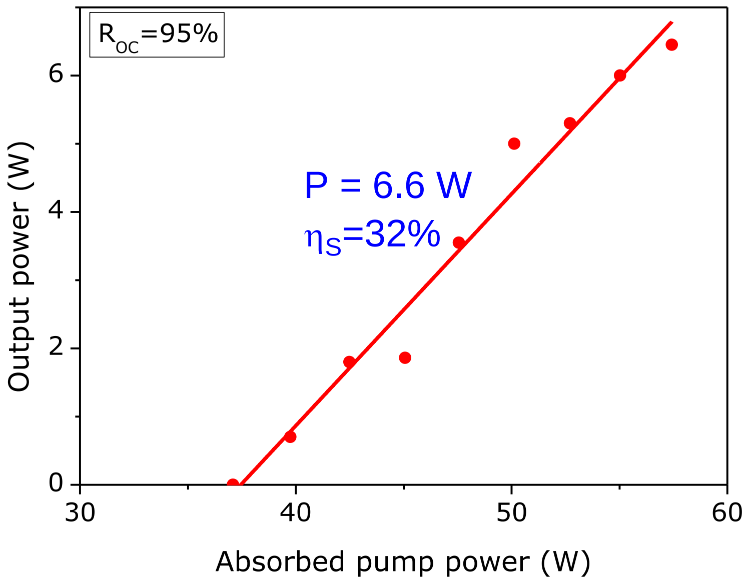
- **NG 0.22 at.% slab 20 x 2 x 2 mm (thin slab)**
- **Significant reflection losses from AR slab faces**



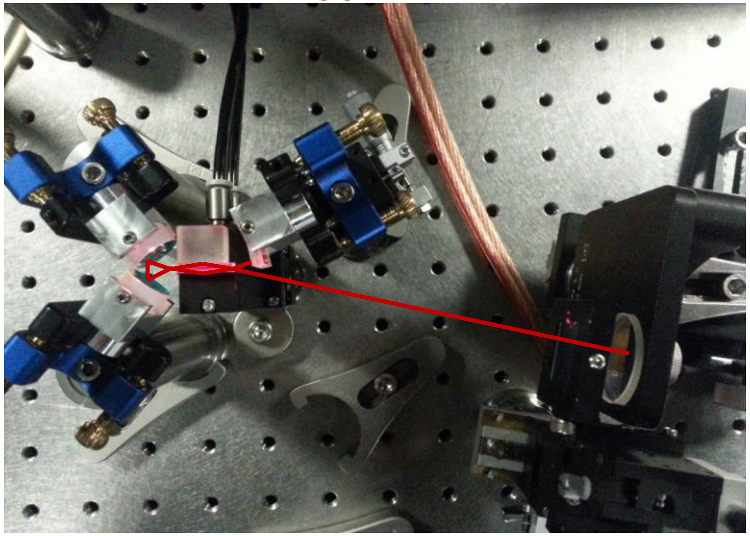
Alexandrite Compact Double-Bounce Laser

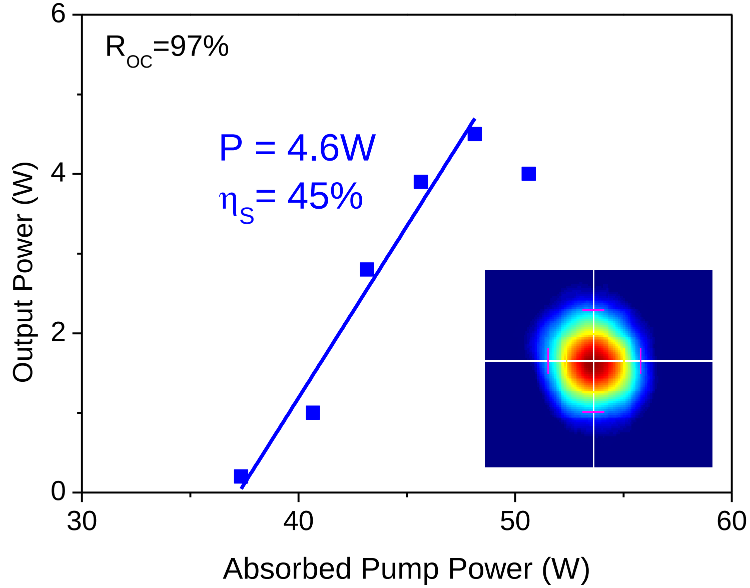
Compact cavity





TEM_{00} cavity





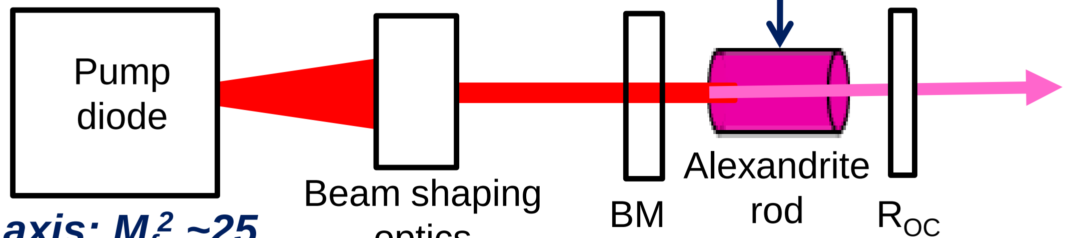
- **Promising approach – minimise losses + enhanced spatial control**

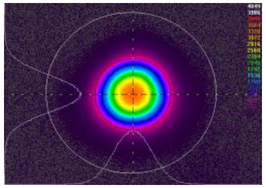
Alexandrite End-Pumped Rod Laser (CW)

Compact cavity

Alexandrite Rod:
ϕ= 4mm; L =10mm
0.13at.% & 0.22at.%Cr

Pump: 60W diode module @ 638nm

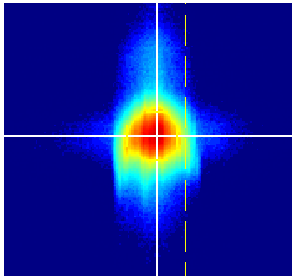




Fast axis: M_f^2 ~25
Slow axis: M_s^2 ~250

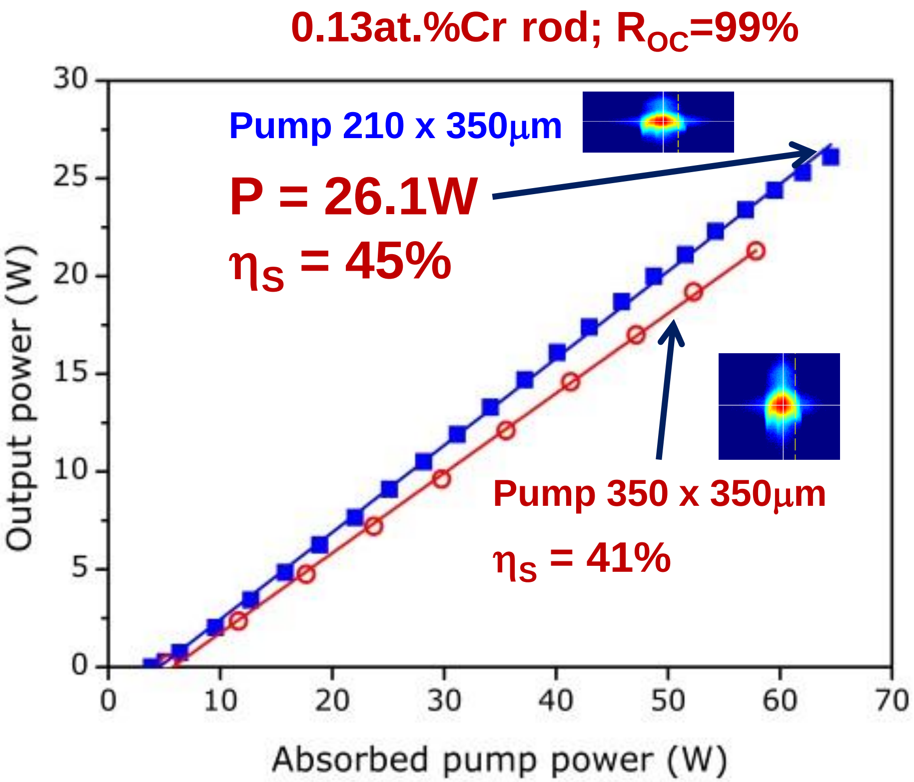
Cylindrical lenses (vertical & horizontal) to resize pump at crystal end face

Dichroic back mirror:
R > 99.9% @755nm
R < 0.2% @638nm



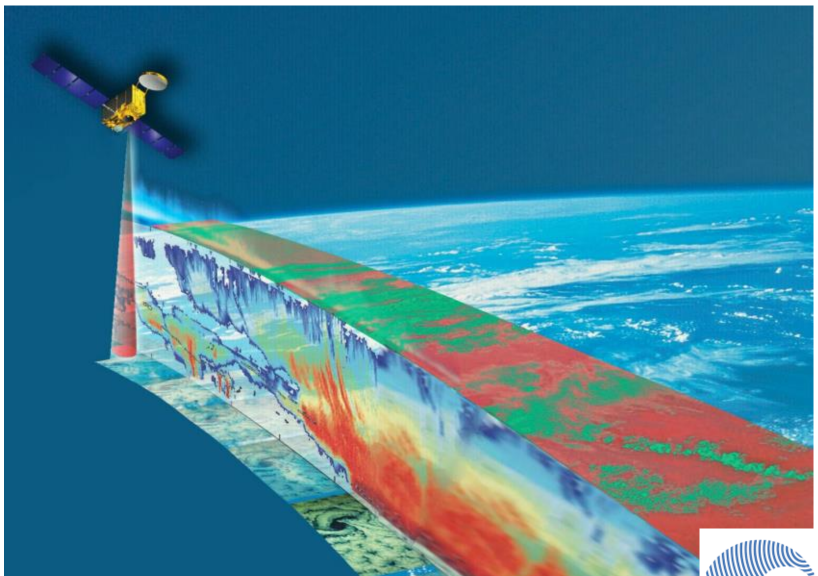
>26W Diode-End-Pumped Alexandrite Rod Laser

Highest Power (*20*x prior end-pumped work)

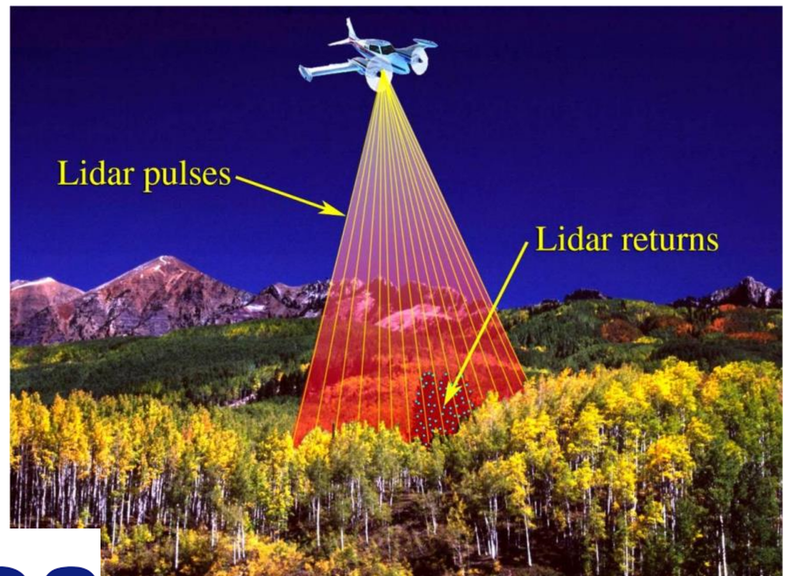


Development of diode-pumped Alexandrite systems

10-100mJ; 100Hz
atmospheric (e.g.cloud/wind) lidar



100μJ; 10kHz; ~ns
altimetry/vegetation lidar



esa

Atmospheric LIDAR Specification

Pulse Energy	100mJ
Pulse Duration	< 100ns
Pulse Repetition Rate	100Hz
Central Wavelength Band	720 – 820nm
Spectral Width	< 0.0001nm (50MHz)
Spatial Beam Quality	$M^2 < 1.5$

Signal-to-noise

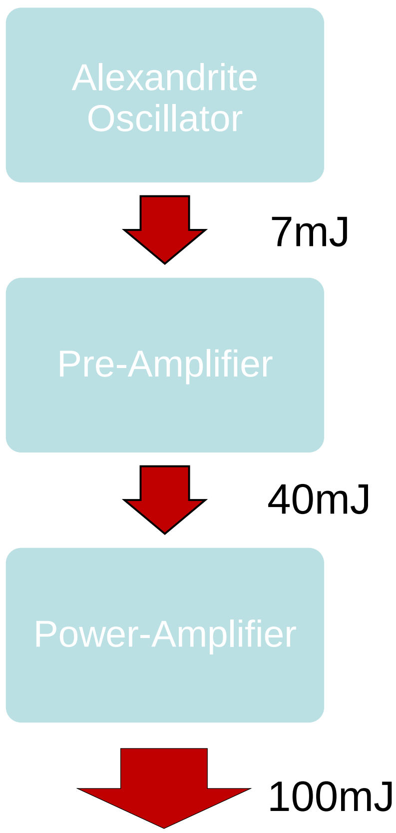
Vertical Resolution

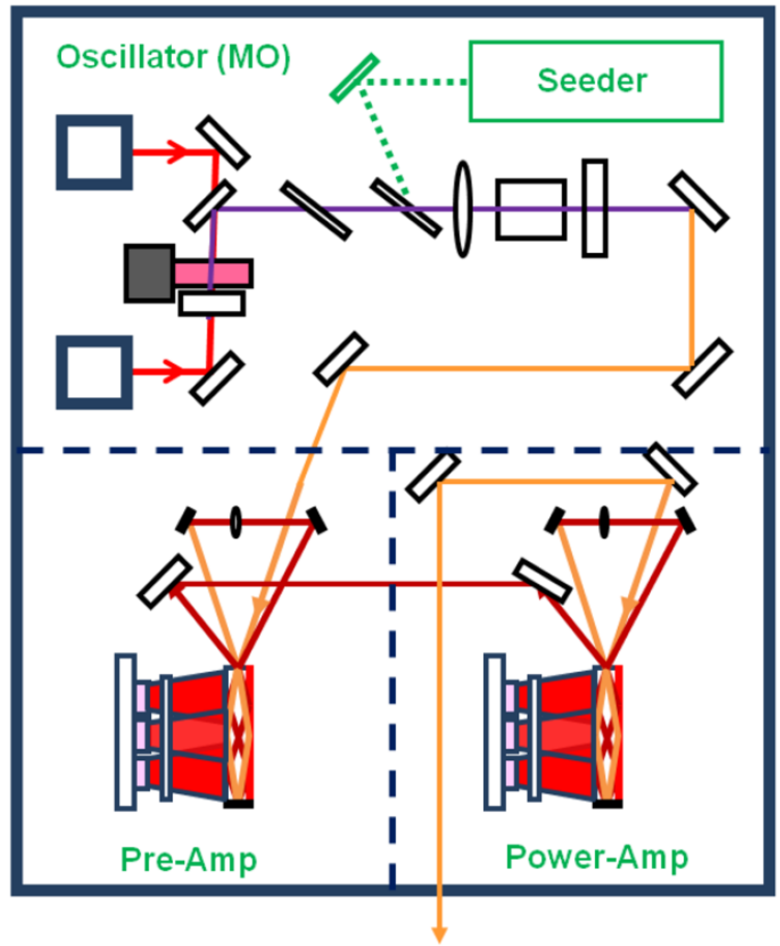
Lateral Resolution

Spectral Resolution

Spatial Resolution

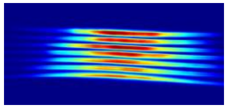
MOPA System Design

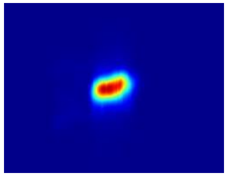


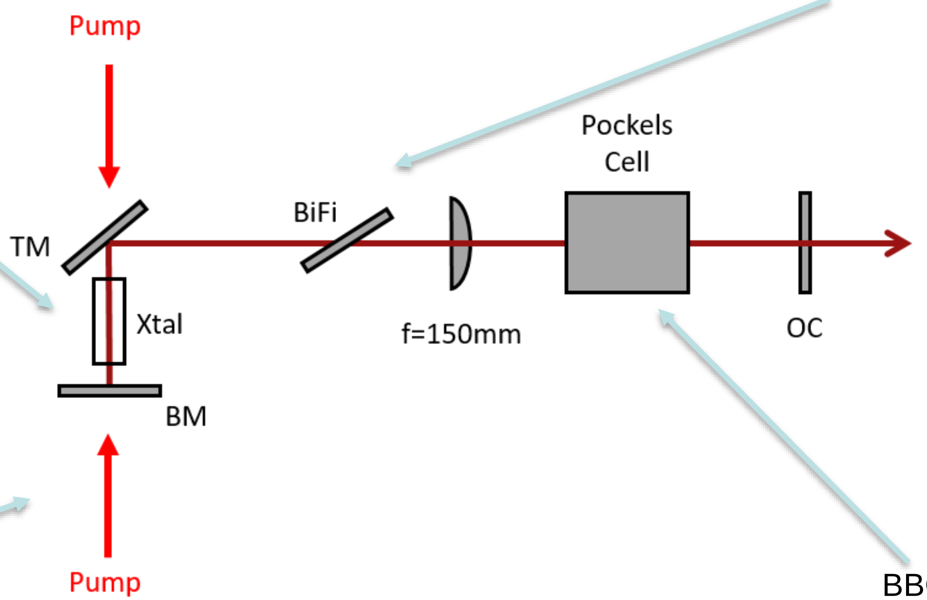


Q-Switched Master Oscillator (MO)
Dual End-Pumped Rod

Alexandrite Rod Crystal
10mm x 4mm
0.22at.% doping





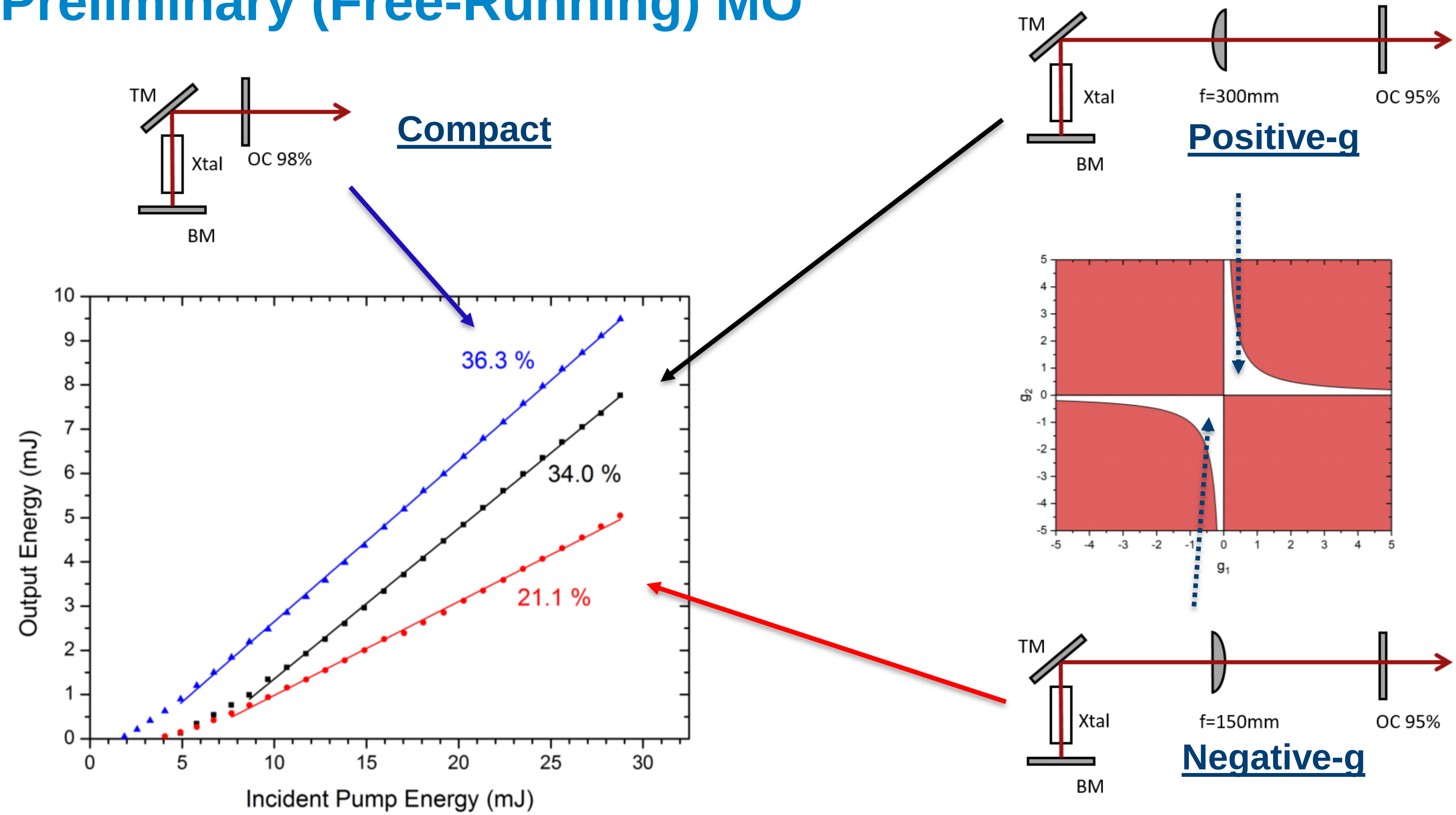


BiFi (Birefringent Filter)
Quartz Plate

Pump Modules
7-Bar Stack
Pulse pumped 100Hz, 200µs
Combined 30mJ
λ ~ 634nm

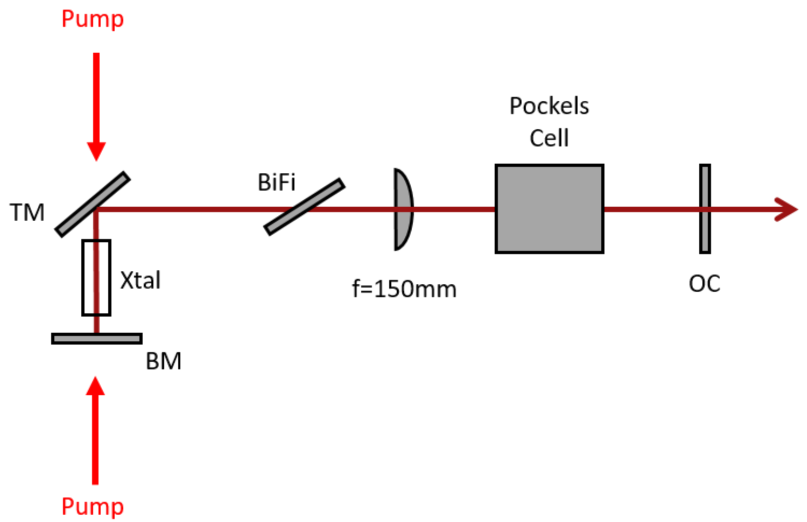
Pockels Cell
BBO (Beta Barium Borate)
Operated at quarter-wave voltage

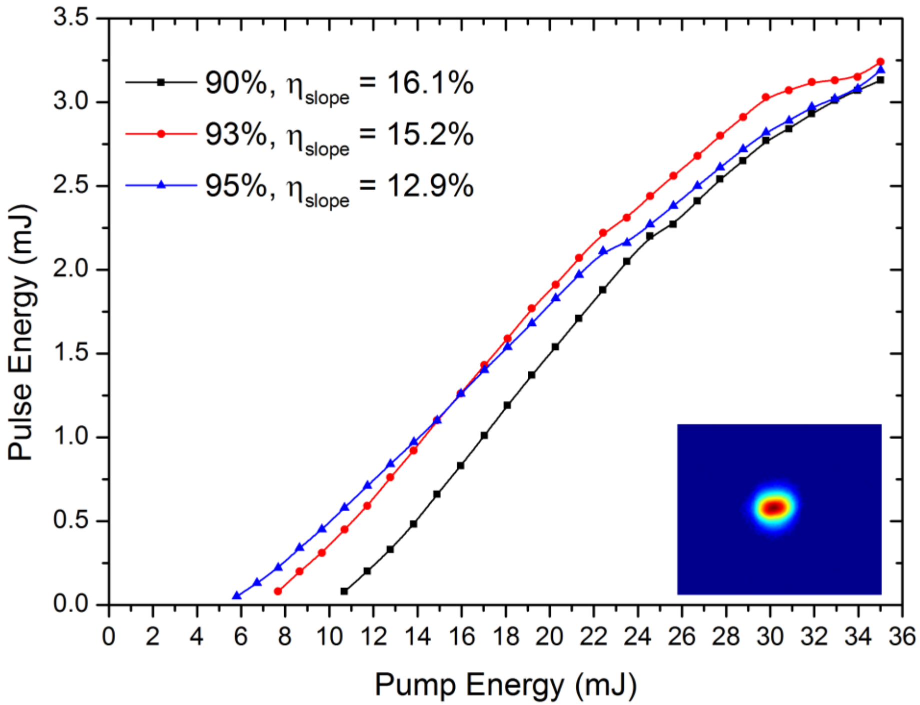
Preliminary (Free-Running) MO



Q-switched MO

Negative-g Cavity

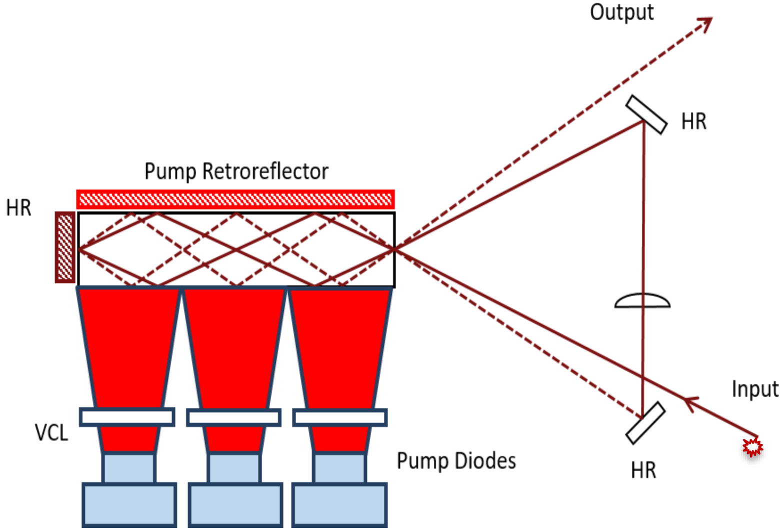




Record: **3.80mJ** @ 50Hz, 250µs pumping

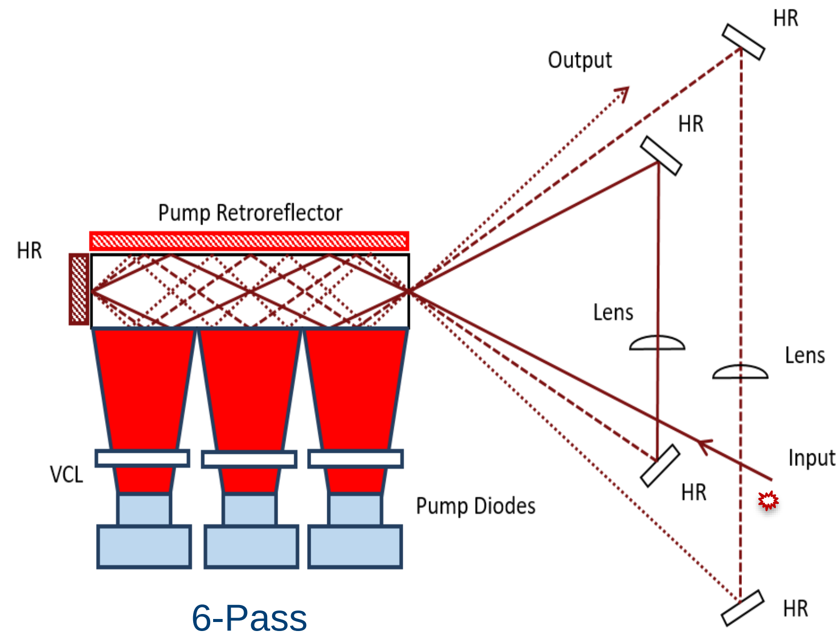
Pulse duration ~ 70 ns

Preliminary Amplifier TEM_{00} Design (4-Pass and 6-Pass)



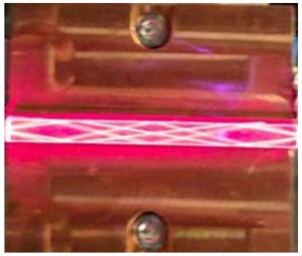
4-Pass

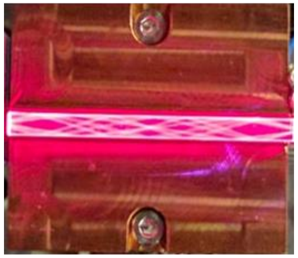
Double Bounce + Triple Bounce



6-Pass

Double Bounce + Triple Bounce + Quadruple Bounce





Vegetation LIDAR Specification

Pulse Energy	0.1mJ (single-photon counting detection)
Pulse Duration	**< 3ns**
Pulse Repetition Rate	10 kHz
Central Wavelength Band	720 – 820nm
Spectral Width	-
Spatial Beam Quality	$M^2 < 1.5$

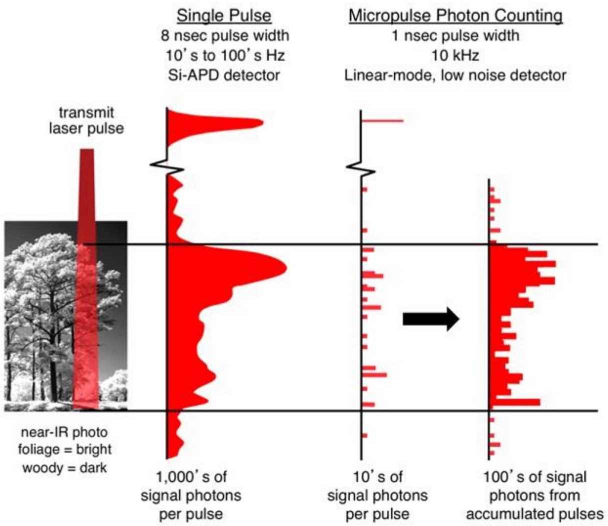
Signal-to-noise

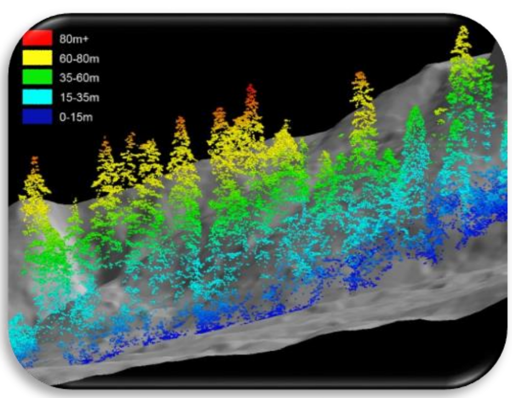
Vertical Resolution

Lateral Resolution

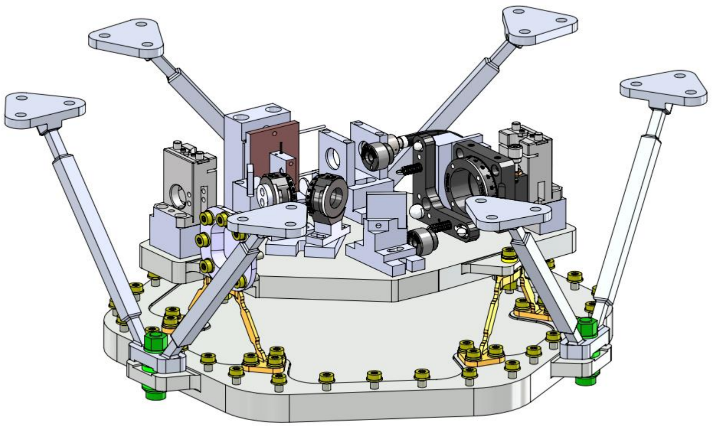
Spectral Resolution

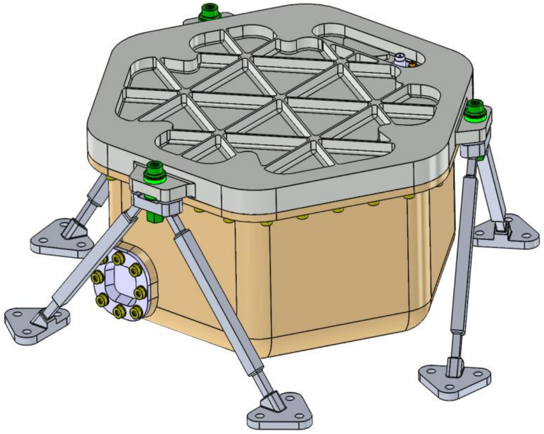
Spatial Resolution



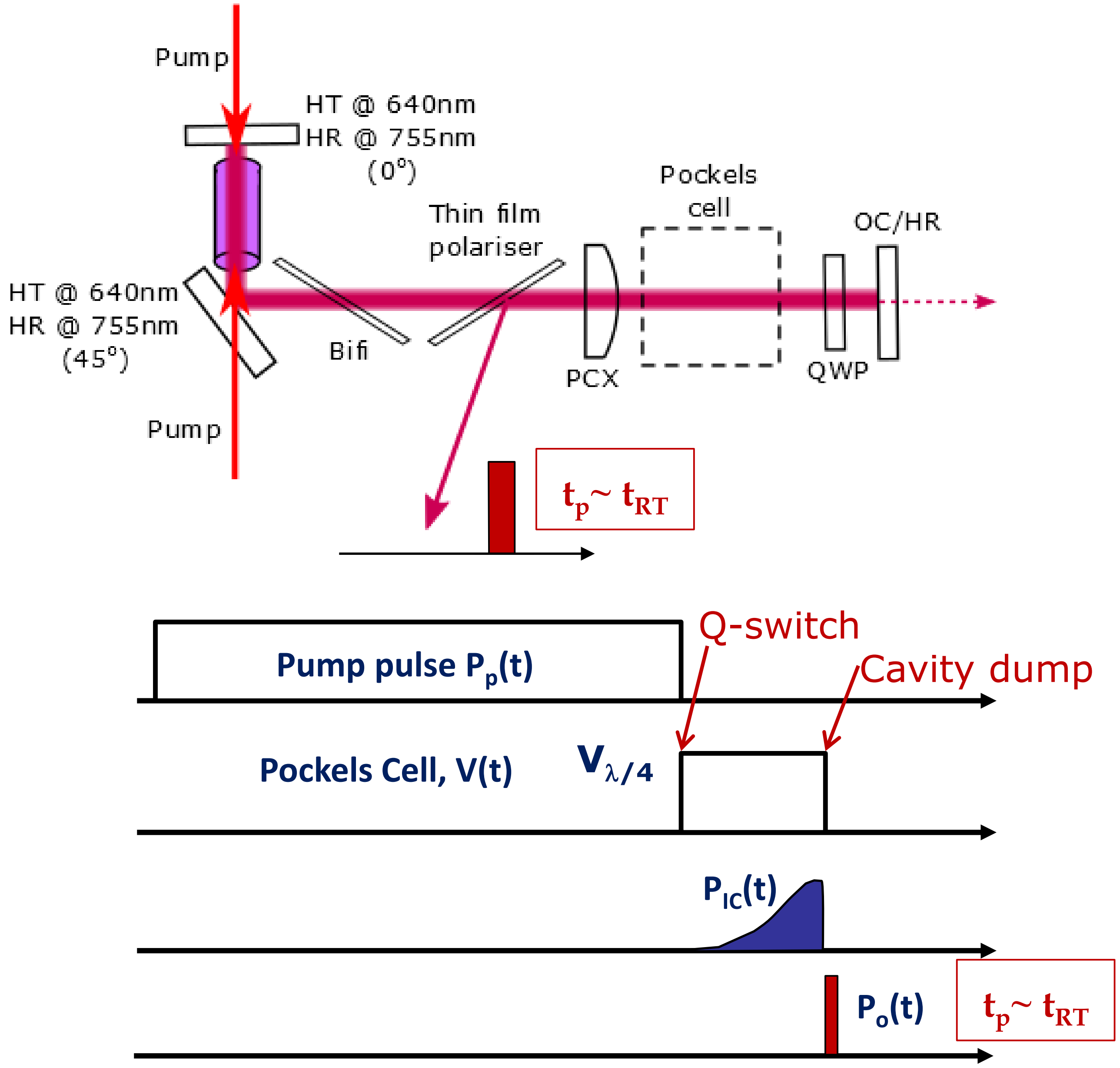


A Space-Engineered Design





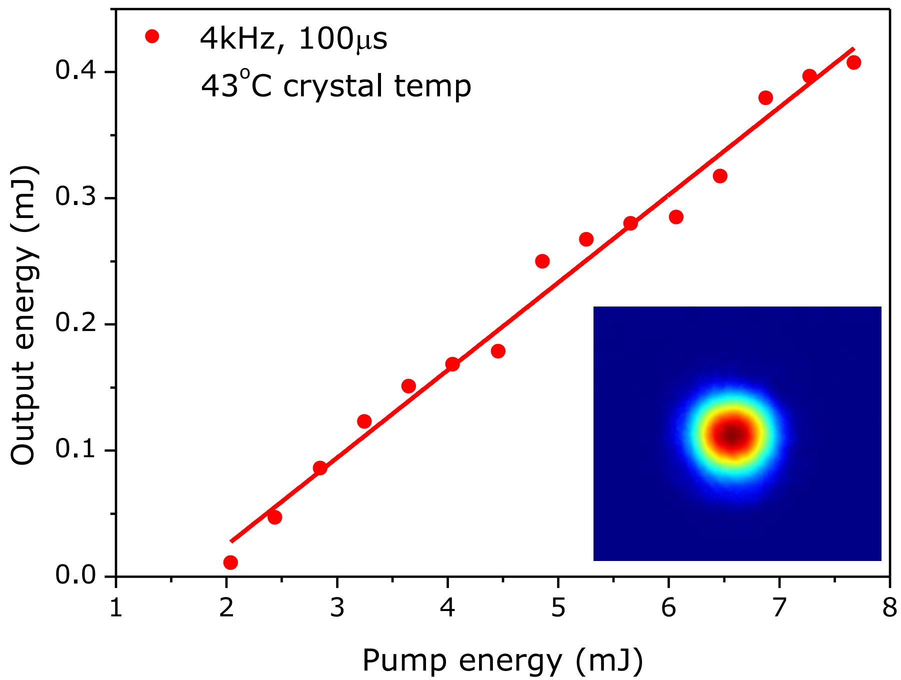
Cavity-dumped Q-switched Laser

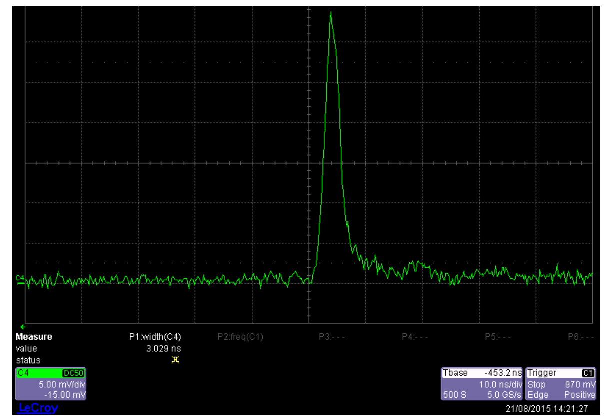


Cavity-dumped Q-switched Laser

Cavity-dumped output: 400 μJ @ 4 kHz

t_p = 3ns (FWHM)!!



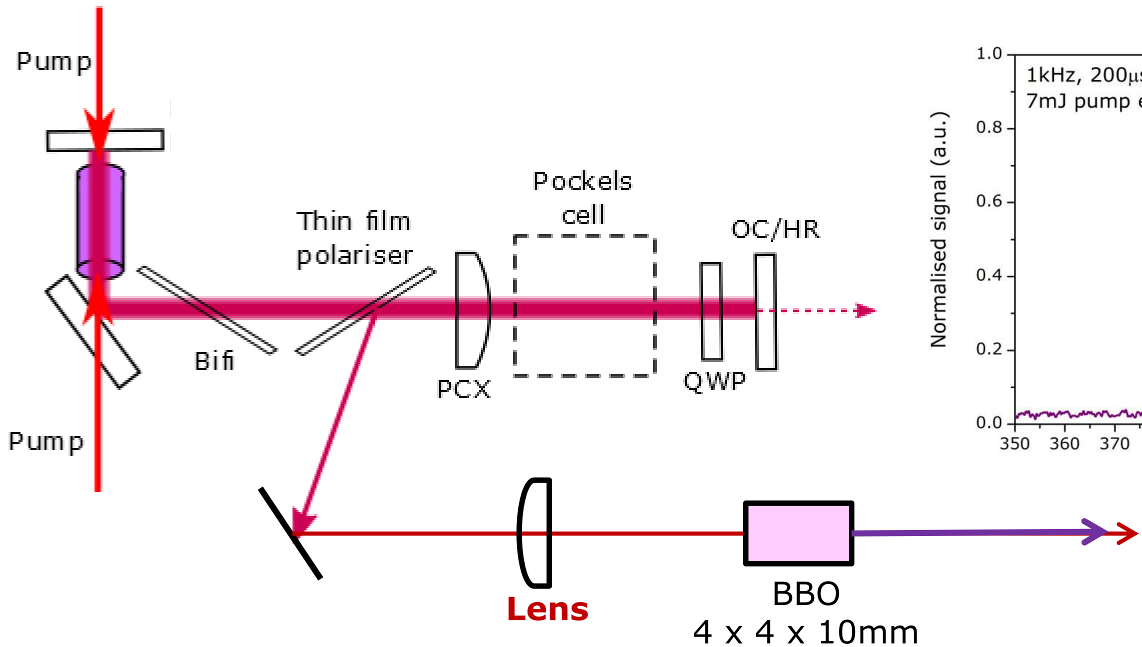


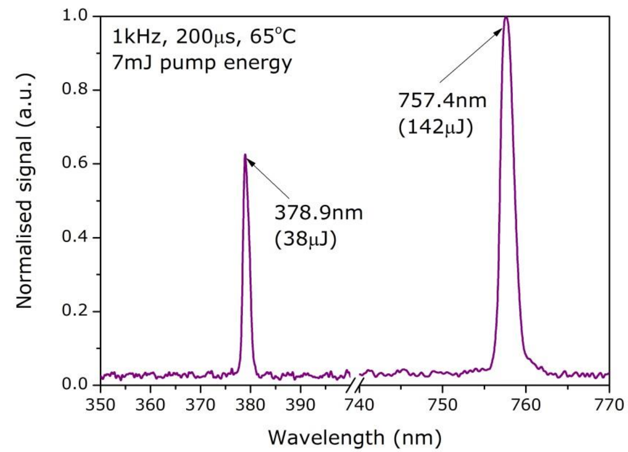
TEM_{00} (M^2<1.2)

CW single end-pumped cavity-dumping:

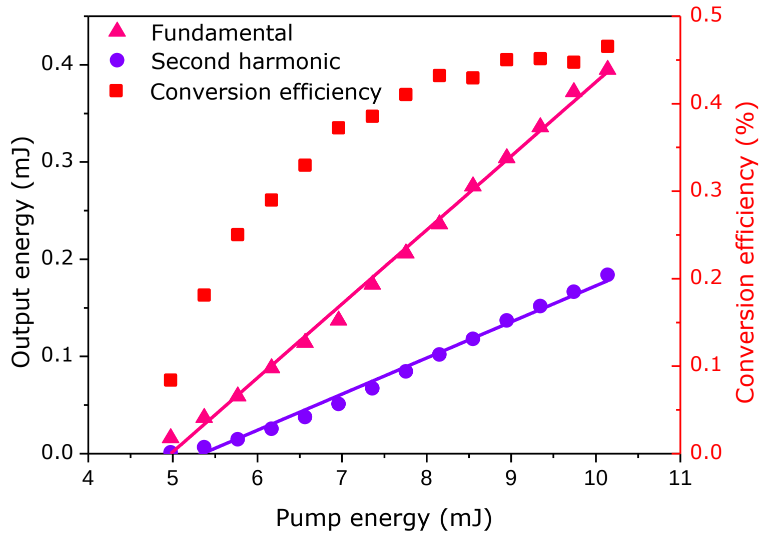
200 μJ @ 10 kHz; t_p = 2.9ns (FWHM); TEM_{00}

SHG of Cavity-Dumped Output

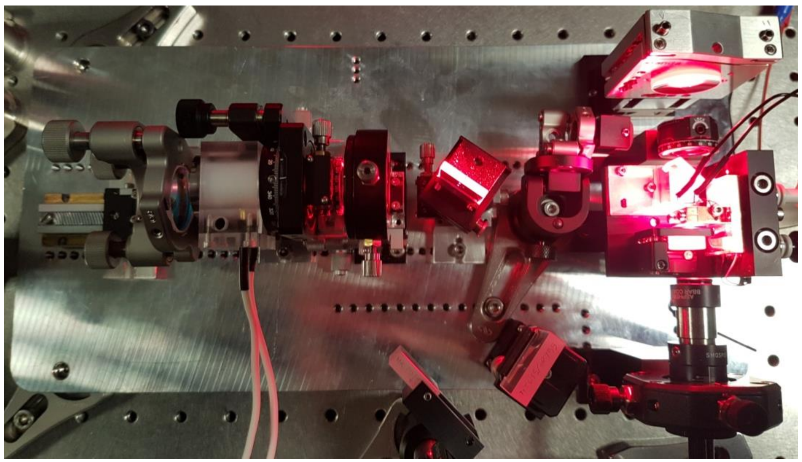


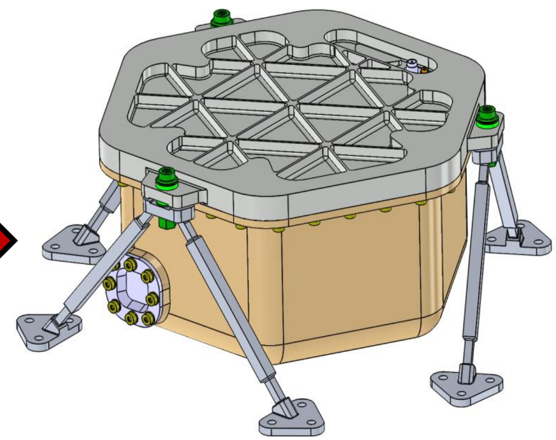


Conversion efficiency = 47%

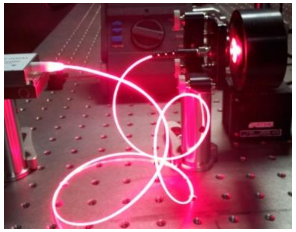


Engineering Development in Progress

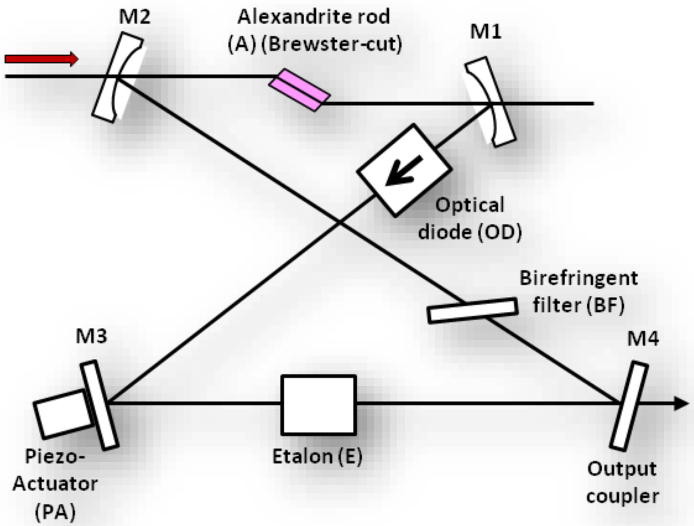


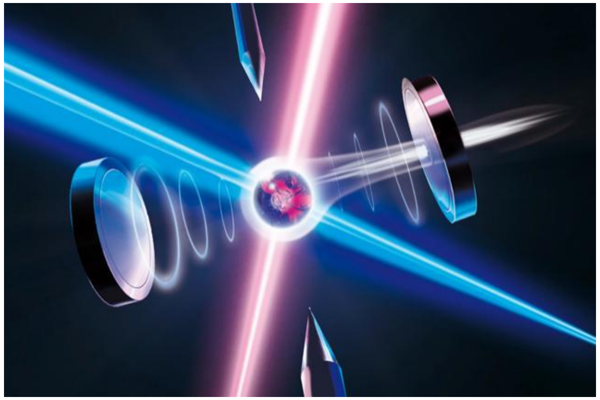


Tunable Narrow-linewidth Alexandrite Laser



RED-DIODE PUMP

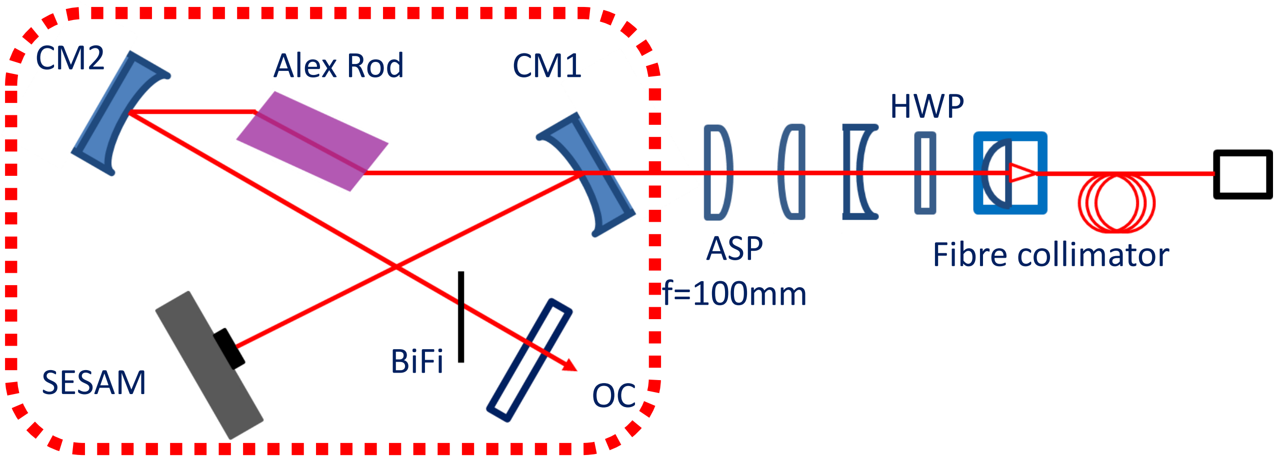




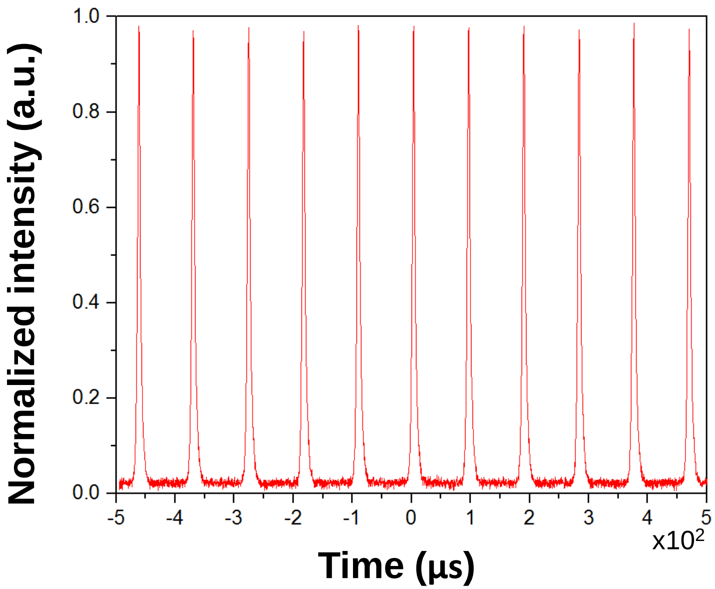
A Low-Cost Alternative to Ti:sapphire

Enabling Quantum Technologies

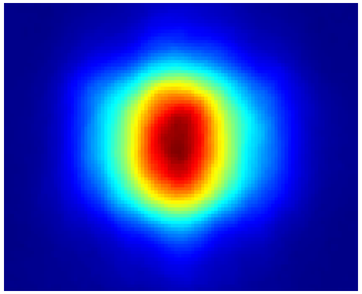
Passively Q-switched Alexandrite Laser



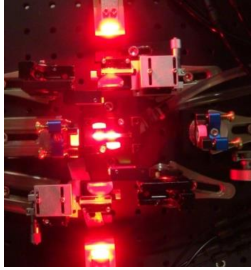
Passively Q-switched pulse train



TEM$_{00}$ M^2<1.1

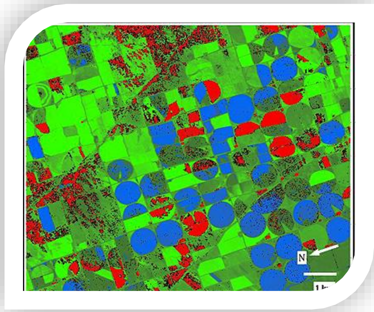


Conclusions



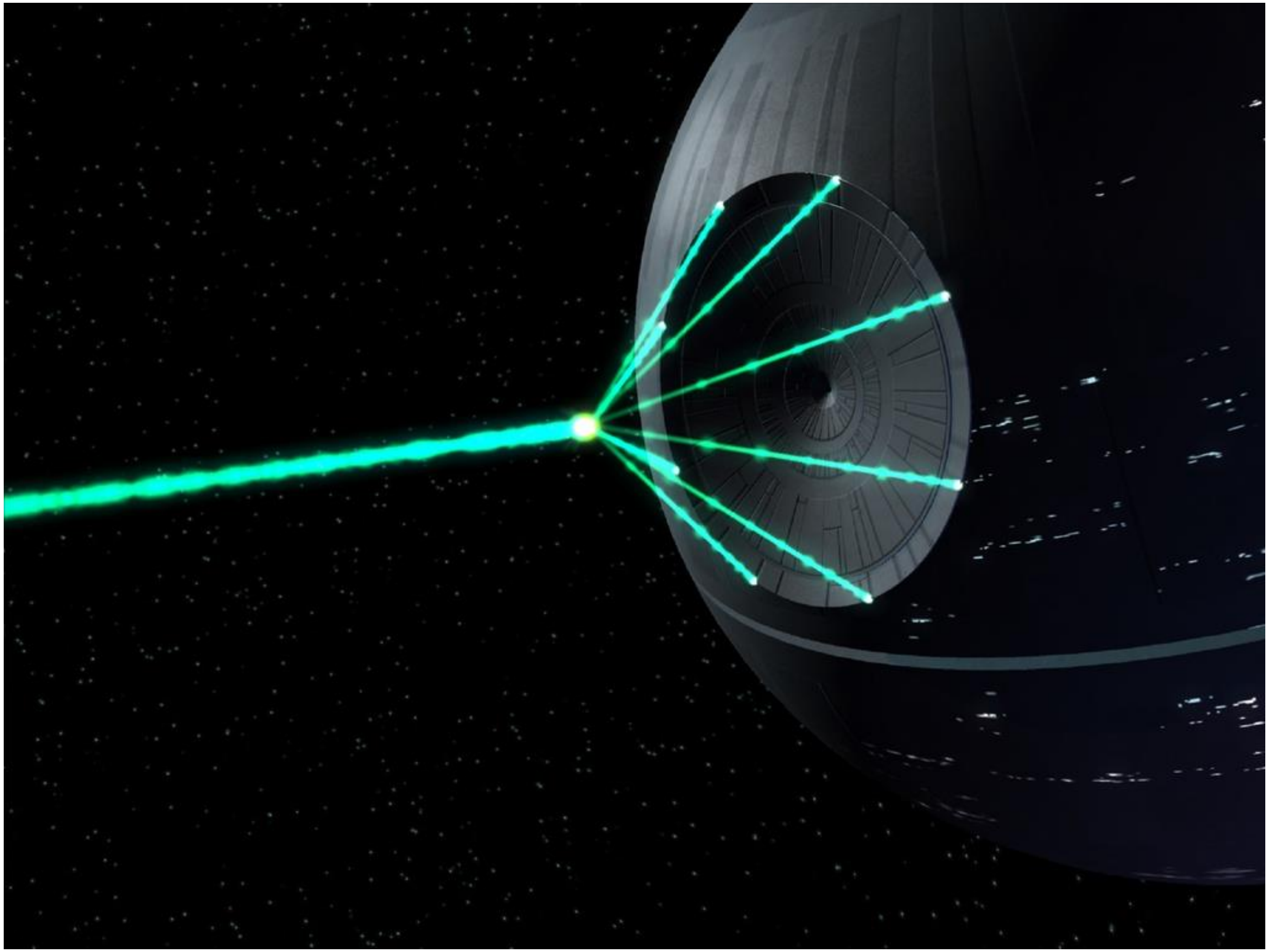
- **First Alexandrite laser Demonstrations & Designs**
  - ➢ *New Knowledge Created*
- **Next steps to raise performance & engineering design**
  - ➢ *Target flexible wavelength lidar missions*

Atmospheric monitoring



Vegetation monitoring

- **In parallel, to look at non-Space Opportunities**
  - ➢ *e.g. Biophotonics + Quantum Technologies*



Coherent Beam Combining
– the next big thing in space lasers?