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Mid-infrared lasers based on transition metal doped II-VI semiconductors

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[2]IPG Photonics Mid-IR Lasers, 1500 1st Ave N, Unit 39, Birmingham, AL 35203, USA, www.ipgphotonics.com/midir
[3]IPG Photonics Corporation, 50 Old Webster Rd, Oxford, MA 01540, USA

The work reported here partially involves intellectual property developed at the University of Alabama at Birmingham (UAB). This intellectual property has been licensed to the IPG Photonics Corporation. The UAB co-authors declare competing financial interests.

2nd Int. Conference on Lasers, Optics & Photonics 09/08/14, Philadelphia, USA

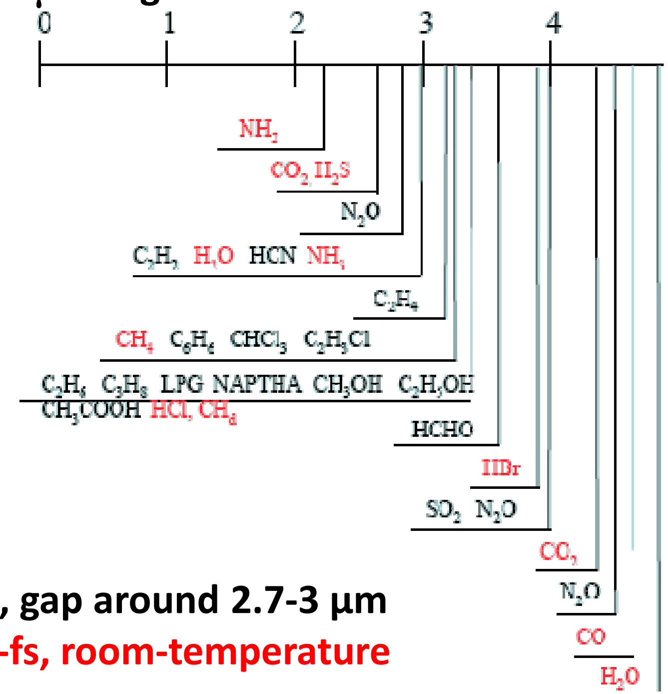
Outline

- Overview, Introduction and Motivation
- What is special about Cr and Fe doped ZnSe/S for mid-IR?
- Spectroscopic properties of Cr and Fe-doped ZnSe/S Gain Media
- Progress in fiber-bulk hybrid mid-IR lasers
  - CW
  - Gain Switched
  - Free-running oscillation
  - Mode-Locked
- Practical applications
- Conclusions and Future Work

Motivation for Cr^{2+}, Fe^{2+} doped ZnSe/S lasers

For molecular time-resolved measurements, molecular spectroscopy, trace gas analysis, biomedical applications, etc. one should directly reach molecular fingerprint 2-20 µm region.

→ **Mid-IR tunable sources are required**

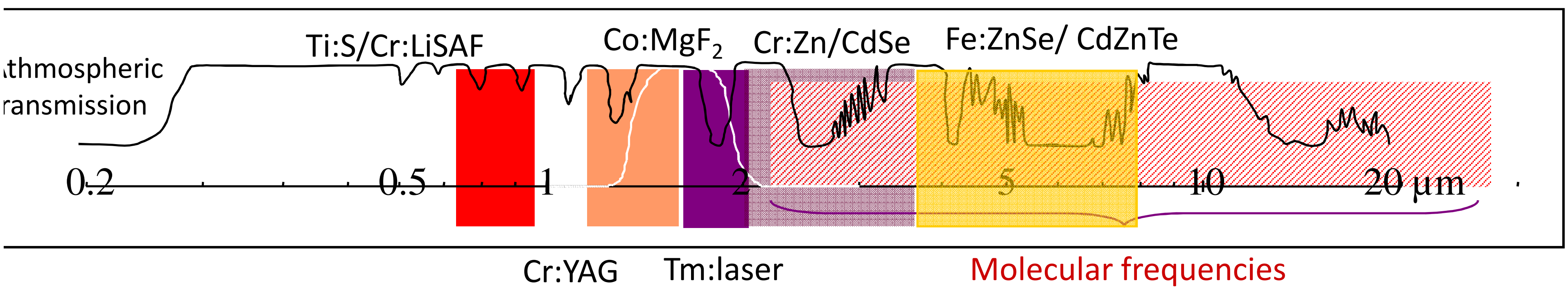


Requirements:

- **Sufficient bandwidth**
- **Low cost, compact, convinient pumping low threshold**
- **High brightness, i.e. good spatial coherence (TEM_{00}).**

Solutions:

- **OPO (bulk ZGP, PPLN, orientation-patterned GaAs):**
  almost ideal solutions, but rather complex and costly
- **QCL: nice solution for λ > 3.4 µm, not as broadband**
- **Semiconductor InGaAsSb/GaSb lasers: narrow tuning, no fs, gap around 2.7-3 µm**
- **Crystalline vibronic lasers: ultrabroadband up to 50 % λ, cw-fs, room-temperature**



What is special about TM^{2+}:II-VI?

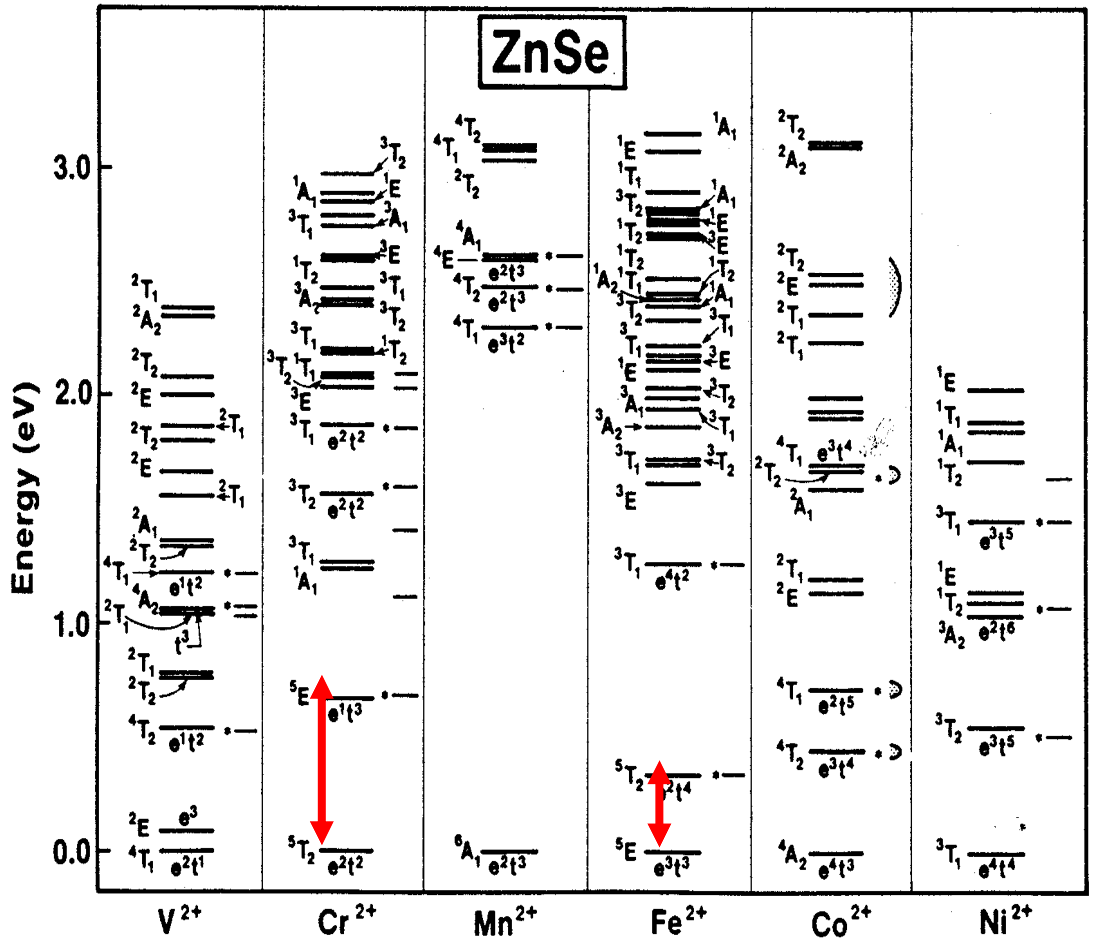
TM (Cr^{2+}, Co^{2+}, V^{2+}, Mn^{2+}, Fe^{2+}, Ni^{2+}) doped II-VI (II-Cd, Zn) (VI- S, Se, Te) compounds have a wide bandgap and possess several important features that distinguish them from other oxide and fluoride laser crystals.

- Chemically stable divalent TM dopant ions, no need for charge compensation.
- Crystallization as tetrahedrally coordinated structures, Tetrahedral coordination (T_d) gives small crystal field splitting, placing the dopant transitions into the IR.
- Optical phonon cutoff occurs at very low energy, maximizing the prospects for radiative decay of mid-IR luminescence in these crystals.

Host	Phonon cut-off ν_{max}, cm^{-1}
ZnTe	210
ZnSe	250
ZnS	350
YAG	850
YLF	560

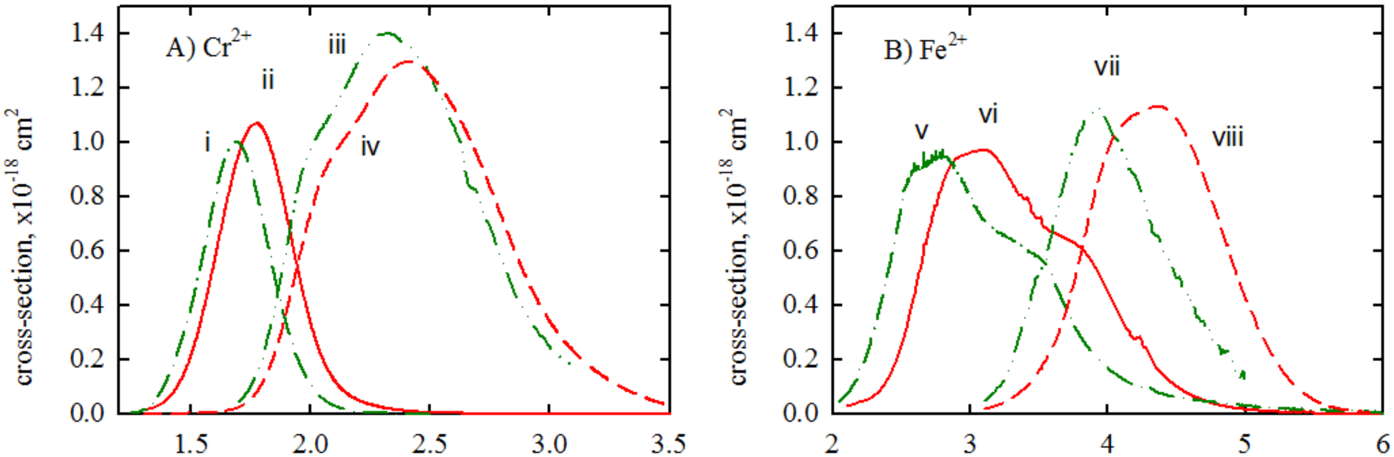
Why Cr^{2+} & Fe^{2+}?

- First excited levels lie at the right energy to generate 2-3 (Cr) & 3.5-5 µm (Fe) mid-IR emission.
- The ground and first excited levels have the same spin, and therefore will have a relatively high cross-section of emission.
- Higher lying levels have spins that are lower than the ground and first excited levels, greatly mitigating the potential for significant excited state absorption at the pump or laser transition wavelengths.
- The orbital characteristics of the ground and first excited levels are different, and will experience a significant Franck-Condon shift between absorption and emission, resulting in broadband "dye-like" absorption and emission characteristics, suitable for a broadly tunable laser.

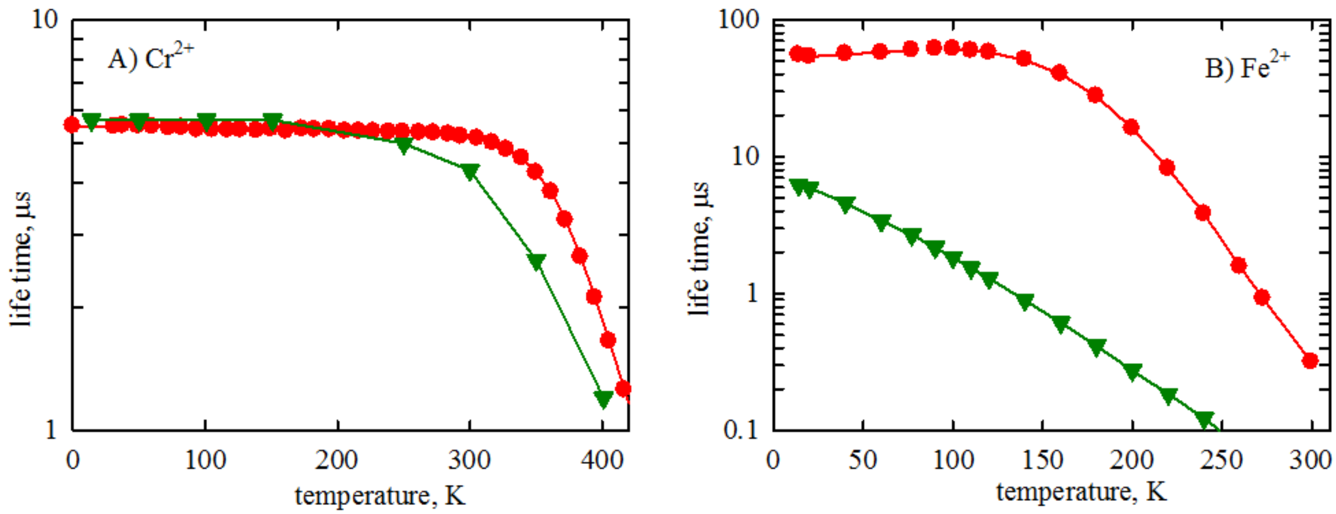


Calculated Multiplet Structure for 3d impurities in ZnSe (after A Fazzio, et al., Phys. Rev. B, 30, 3430 (1984)

Spectroscopic properties of Cr and Fe doped ZnSe/S compounds



A) Absorption (Cr:ZnS- curve i; Cr:ZnSe-curve ii) and emission (Cr:ZnS- curve iii; Cr:ZnSe-curve iv) cross-sections of Cr^{2+} ions in ZnS and ZnSe; B) Absorption (Fe:ZnS- curve v; Fe:ZnSe-curve vi) and emission (Fe:ZnS- curve vii; Fe:ZnSe-curve vii) cross-sections of Fe^{2+} ions in ZnS and ZnSe.



Luminescence lifetime versus temperature for chromium (A) and iron (B) doped ZnS (triangle) and ZnSe (circle) crystals.

S. Mirov, V. Fedorov, D. Martyshkin, I. Moskalev, M. Mirov and S. Vasilyev, "Progress in Mid-IR Lasers Based on Cr and Fe Doped II-VI Chalcogenides,"
J. Special Topics in Quantum Electronics, submitted April 2014.

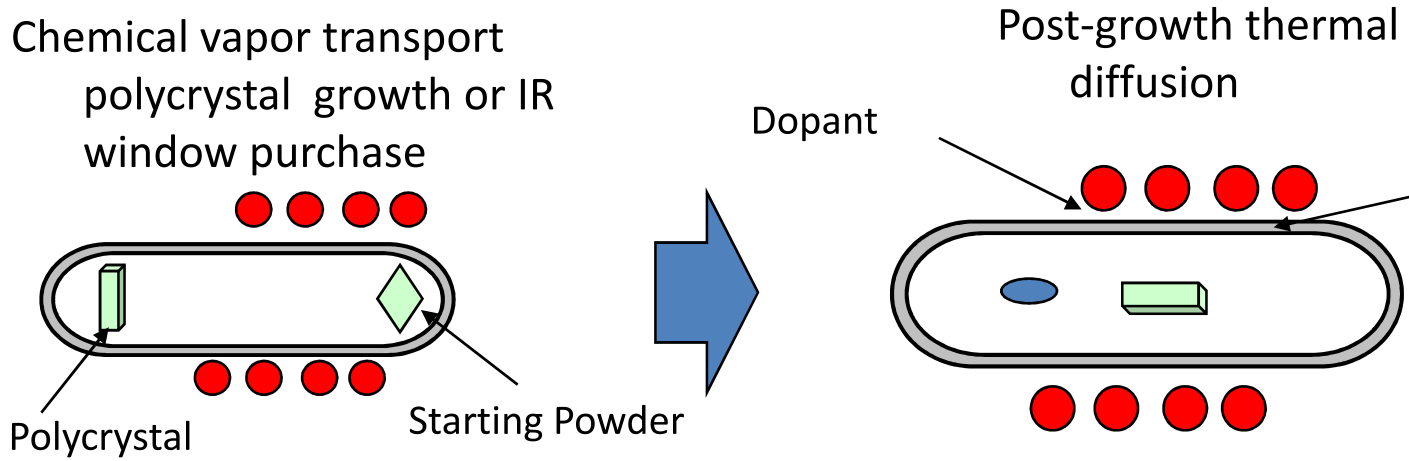
Challenges of Bulk Crystal Fabrication

- Bridgman technique (sublimation of chemicals requires simultaneous use of high temperature and pressure, (1550C & 75 atm – economical viability?)
- Chemical vapor transport (CVT) (doping is very difficult)
- Physical vapor transport methods (PVT) (doping is very difficult)
- Hot-pressed ceramics
- The post-growth thermal diffusion doping of ZnSe/S ceramics
- Pulsed laser deposition
- Nano & micropowders, composite II-VI-liquid, II-VI-polymer and II-VI-glass gain media

Key challenges:

- Hard to get high Cr concentration
- Hard to get uniform Cr distribution
- Hard to make large Cr^{2+}:ZnSe crystals
- High scattering losses
- Low damage threshold
- Strong thermal lensing effects

Bulk Crystal Preparation by a Quantitative Post-growth Thermal Diffusion

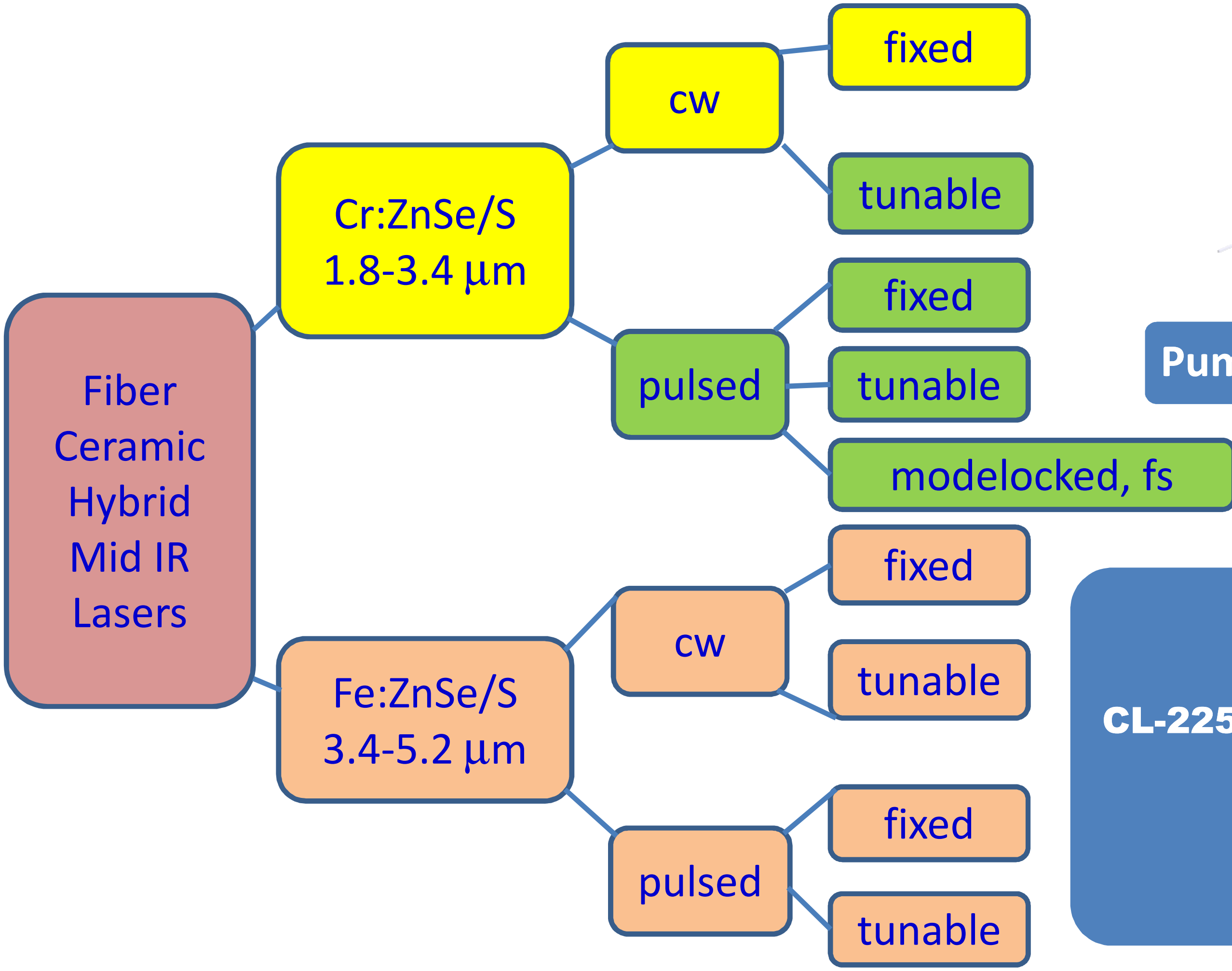


- $P=10^{-5}$ Torr
- T= 950-1000 C
- t=3-10 days

- Fast diffusion of dopant with suppressed sublimation in Zn and Se sub-latticies
- Low scattering loss (1-2 % per cm) in thermally diffusion doped crystals
- Uniformly-doped, reasonably large samples up to 7 mm thickness
- Quantitative technology enabling pre-assigned concentration of dopant with accuracy better than 3%
- Good for High-Power (tunable) Lasers

S.B. Mirov, V.V. Fedorov, (November 1, 2005) Mid-IR microchip laser: ZnS:Cr^{2+} laser and saturation absorption material", *US Patent* No 6,960,486.

Fixed Frequency Wavelength Converter

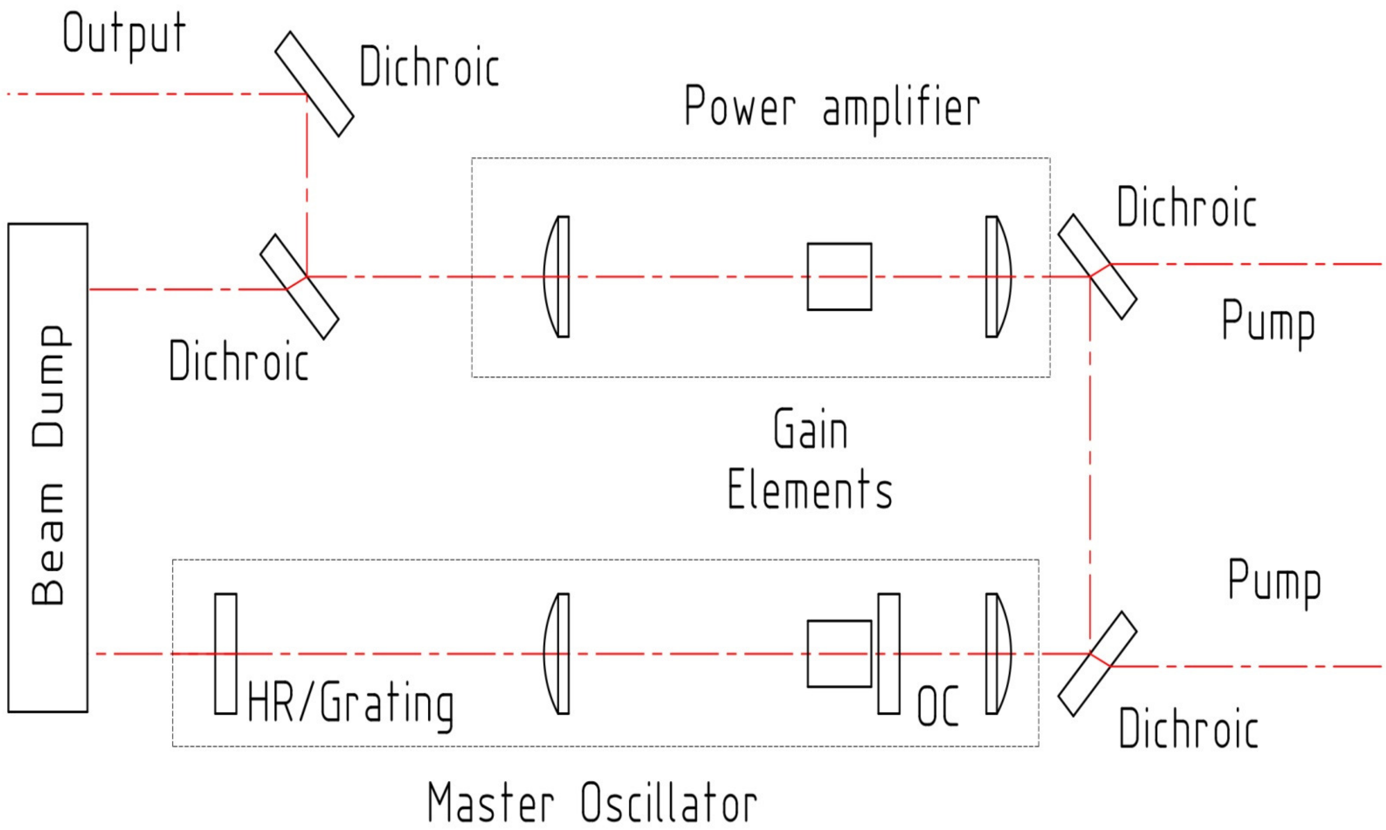


Pumped by Er or Tm fiber laser

CL-2250-5

- multi-Watt output power
- fixed wavelength
- output wavelength range: 2000 - 3000 nm

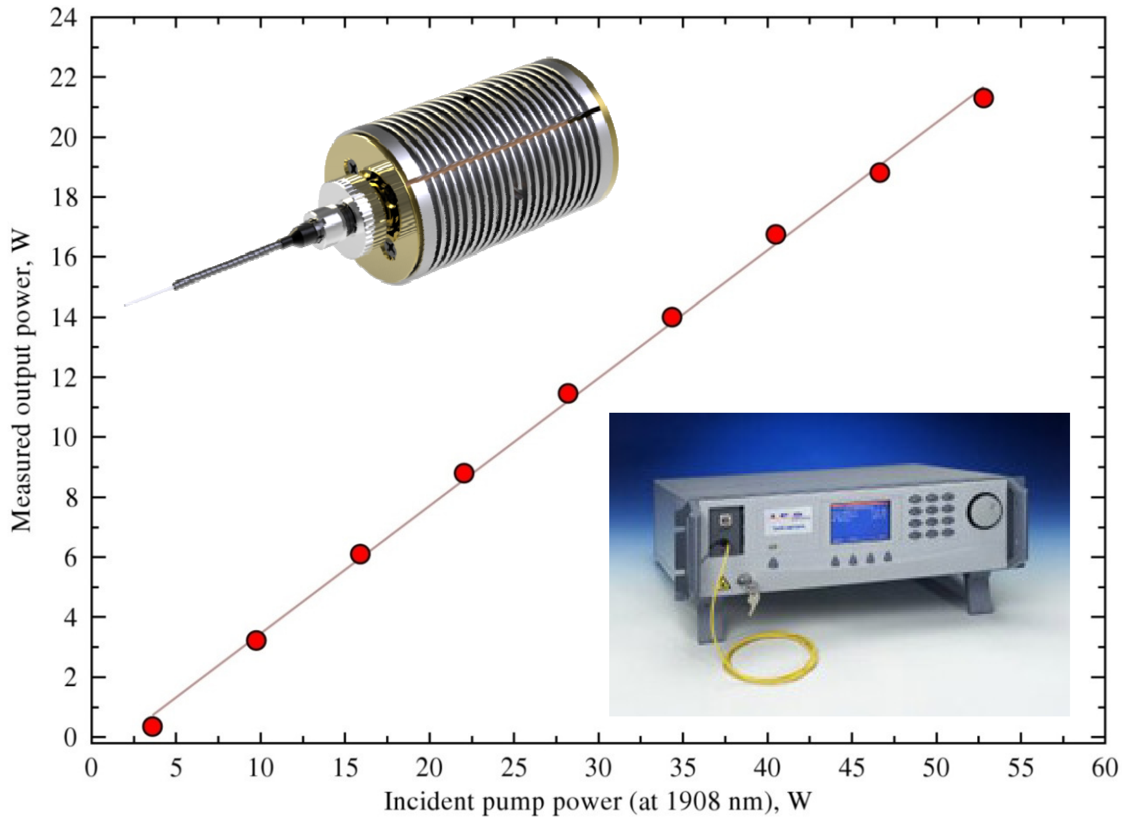
Optical scheme of high-power tunable Cr^{2+}:ZnS and Cr^{2+}:ZnSe CW MOPA systems based on linear cavity design



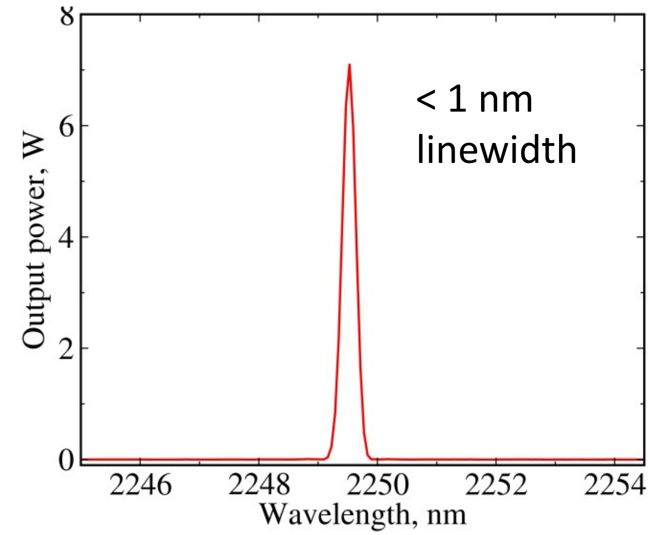
CL-2250-20

Fixed Frequency Mid IR Wavelength Converter

- multi-Watt output power
- fixed wavelength
- output wavelength range: 2000 - 3000 nm

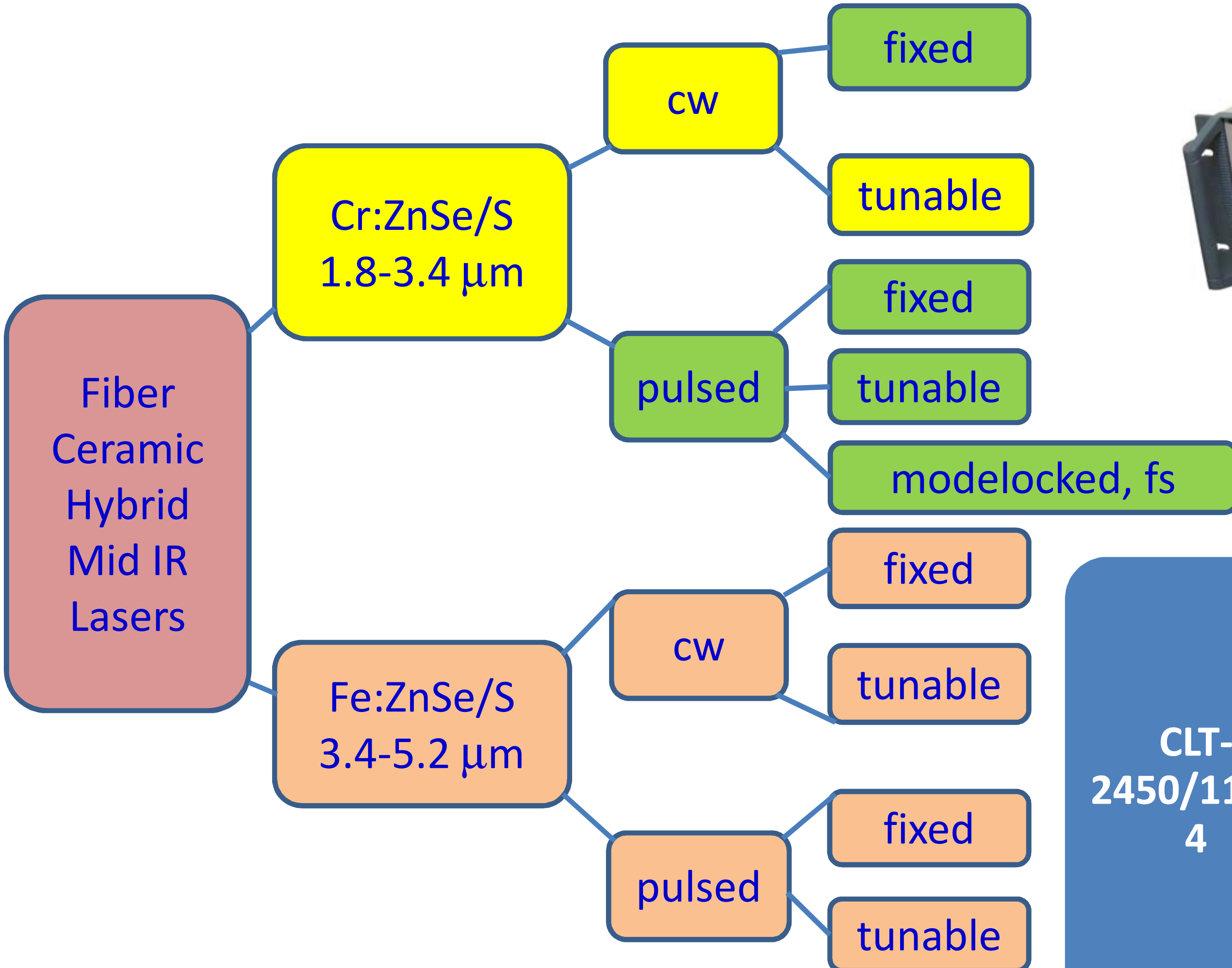


Typical Output Spectrum



- Plastics Cutting, Welding, Marking, Drilling
- Tissue & Bone Cutting
- Dental Applications
- Skin Rejuvenation

CW Tunable Cr:ZnSe/S Laser



CLT-2450/1100-4

- cw output, 20 mW to >10 Watt
- typical linewidth < 0.5 nm, < 0.1 nm available
- up to 1100 nm tunable range
- any central wavelength within 2-3µm
- TEM_{00} , $M^2 < 1.2$

IPG PHOTONICS

CW Tunable Cr:ZnSe/S Laser

CLT-2450/1100-4

- cw output, 20 mW to >10 Watt
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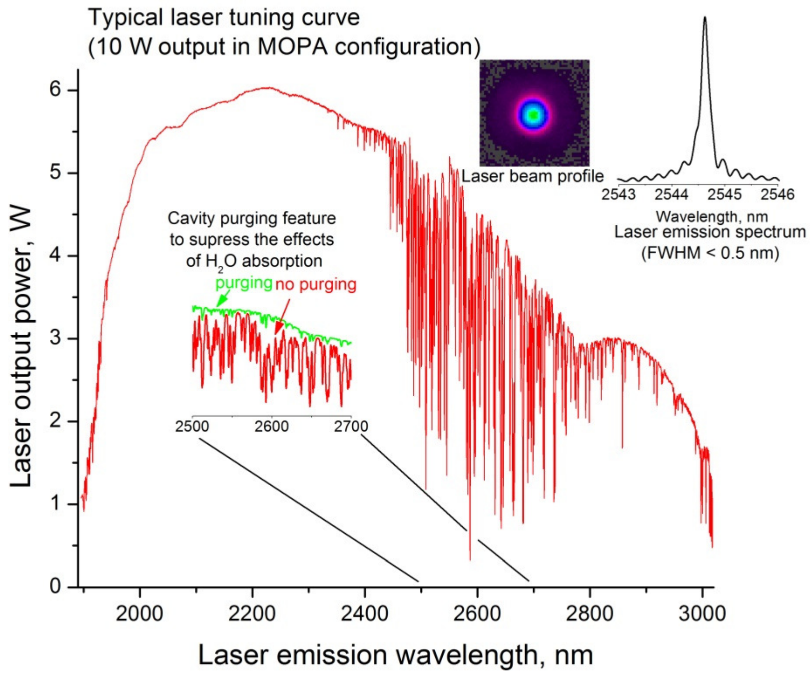
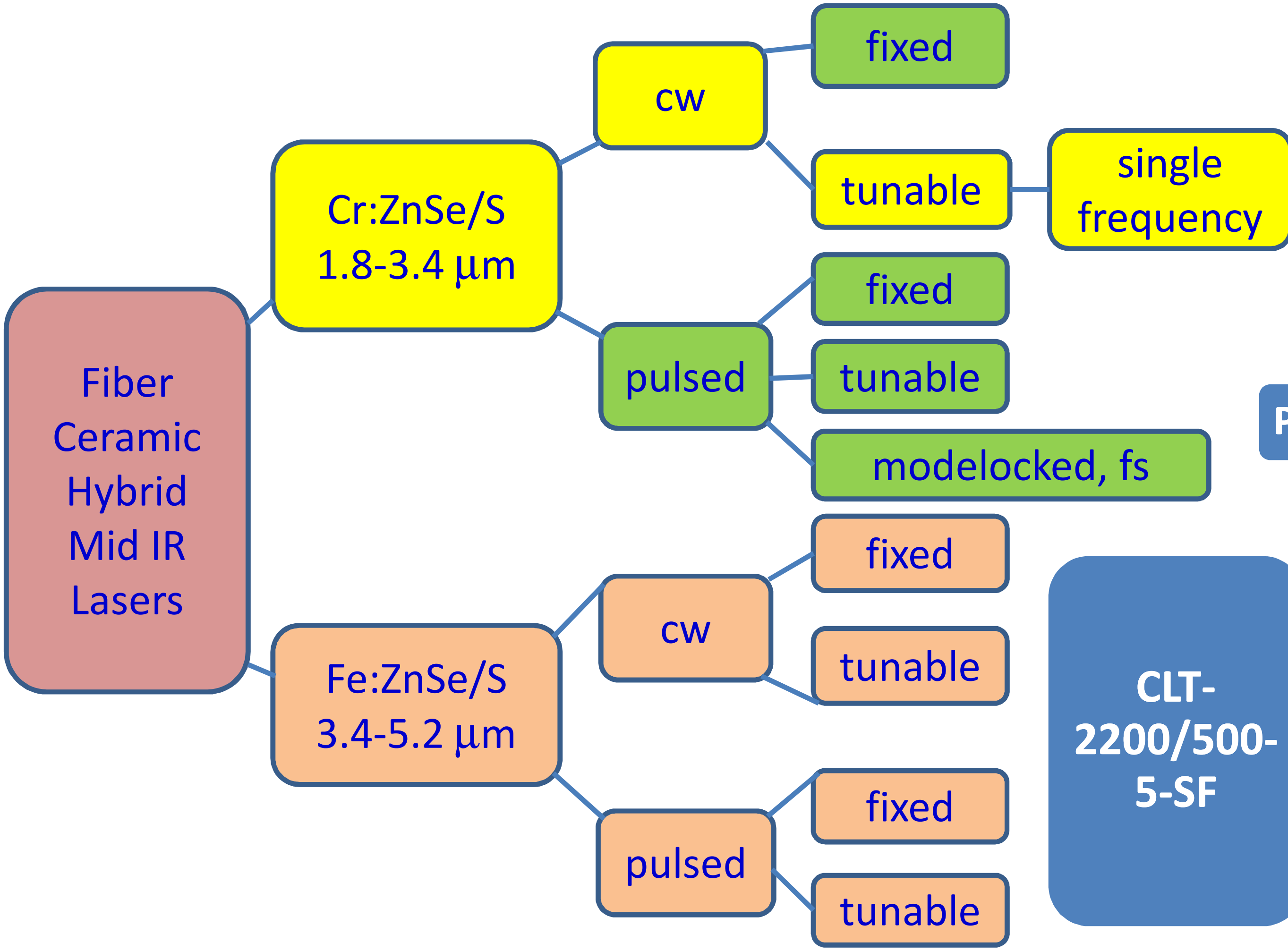


- Spectroscopy
- OPO Pump Source
- Medical Applications
- Environmental Monitoring
- Industrial Process Control
- Material processing

Single-Frequency CW Tunable Laser



Pumped by Er fiber laser

CLT-2200/500-5-SF

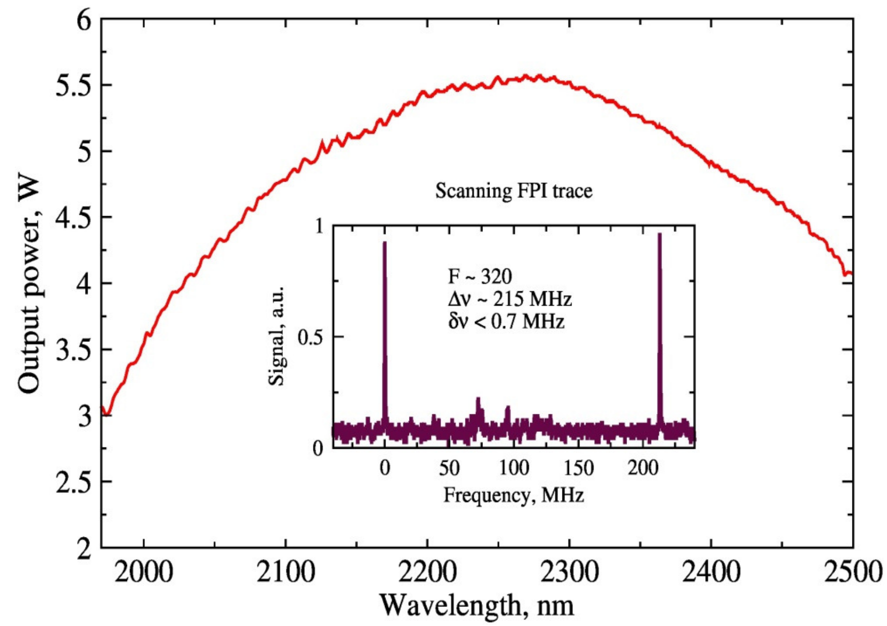
- multi Watt output power
- narrow linewidth, <1 MHz
- large tuning range with a single set of optics (any wavelength within 2000 - 3000 nm tuning range)

IPG PHOTONICS

CLT-2200/500-5-SF

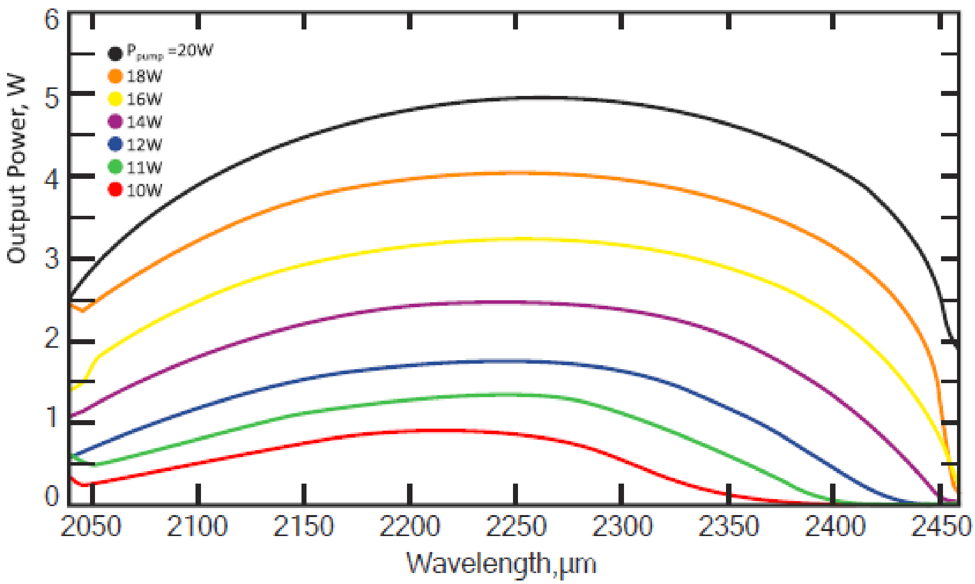
Single-Frequency CW Tunable Laser

- multi Watt output power
- narrow linewidth, <1 MHz
- large tuning range with a single set of optics (any wavelength within 2000 - 3000 nm tuning range)



Output power vs wavelength of a tunable single-frequency Cr^{2+}:ZnS/Se laser system. The insert shows an interferogram obtained with high-resolution ring interferometer

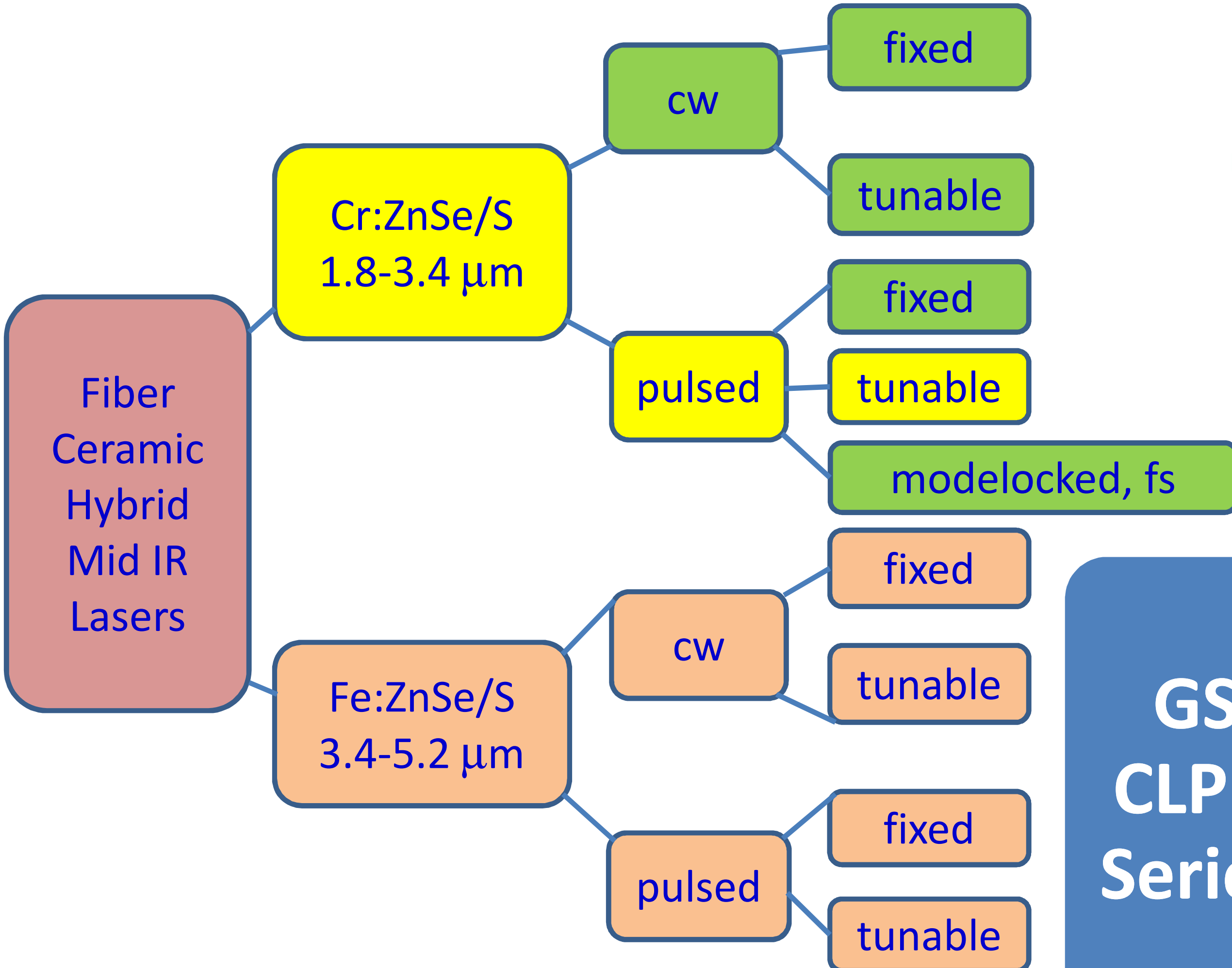
Output Power vs Wavelength for Different Levels of Pump Power



- High Resolution Spectroscopy
- OPO Pump Source
- Industrial Process Control
- Medical Applications
- Material processing
- Environmental Monitoring
- Free Space Communications

IPG PHOTONICS

Gain-Switched Pulsed Tunable Cr:ZnSe/S Lasers



GS CLPN Series

- Tunability 2300-3000 nm
- Pulsed output energy up to 10 mJ
- Pulse duration 2-20 ns
- Linewidth <0.5nm
- Repetition rate 0.1-1 kHz
- TEMoo

IPG PHOTONICS

Gain-Switched Cr:ZnSe/S Lasers. CLPN Series

Gain-switched Tunable Cr:ZnSe Laser

- Tunability 2300-3000 nm
- Pulsed output energy up to 10 mJ
- Pulse duration 2-20 ns
- Linewidth <0.5 nm
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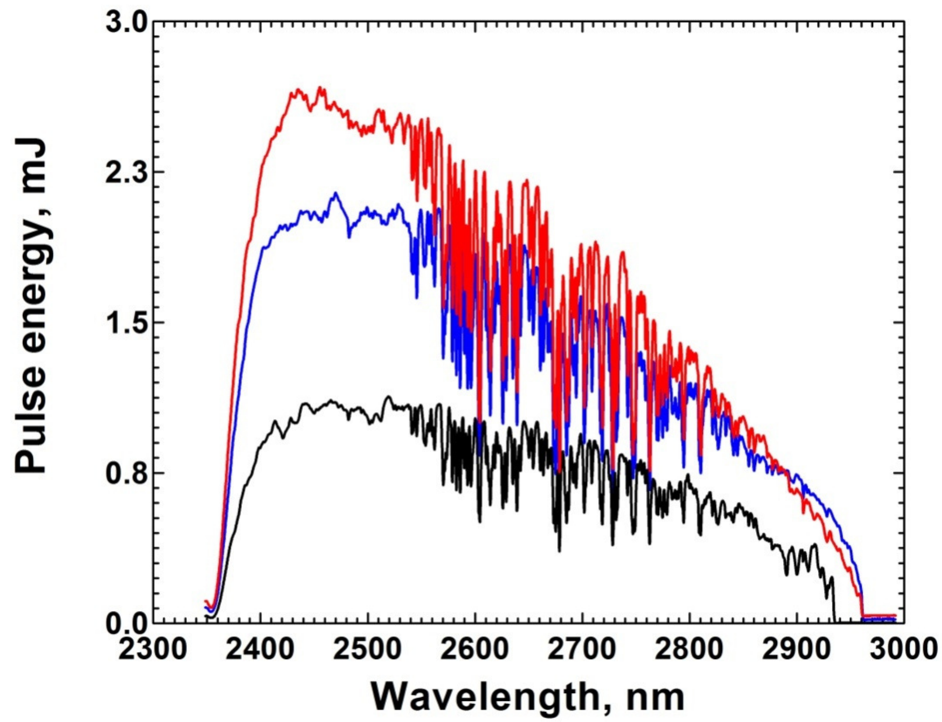
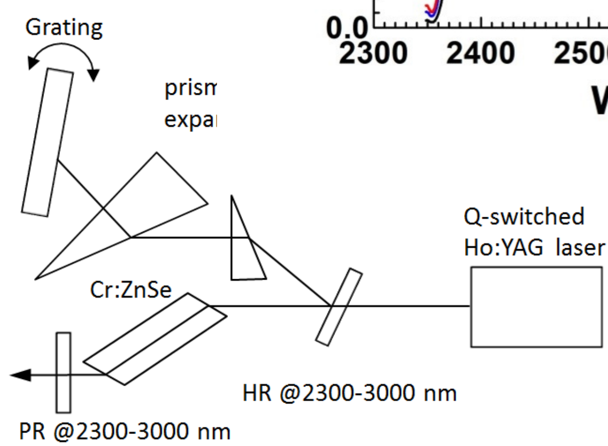
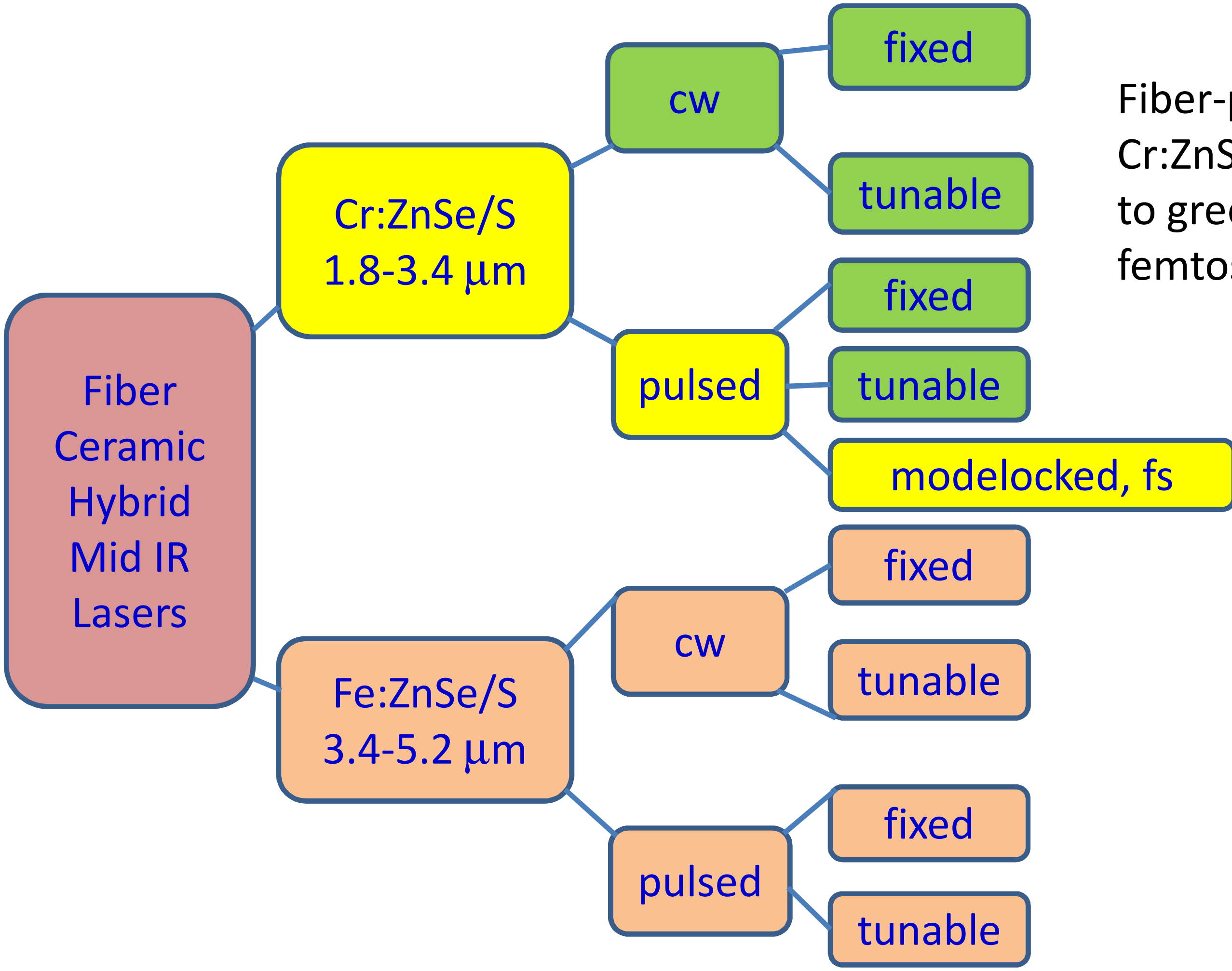
- TEMoo





- Laser skin treatment
- Laser scalpel
- Material processing

Ultrafast Mid IR Lasers



Fiber-pumped mode-locked Cr:ZnS/Se lasers are very similar to green-laser pumped femtosecond Ti:sapphire lasers.

transient absorption spectroscopy

2D IR spectroscopy

2 and 3 photon bioimaging

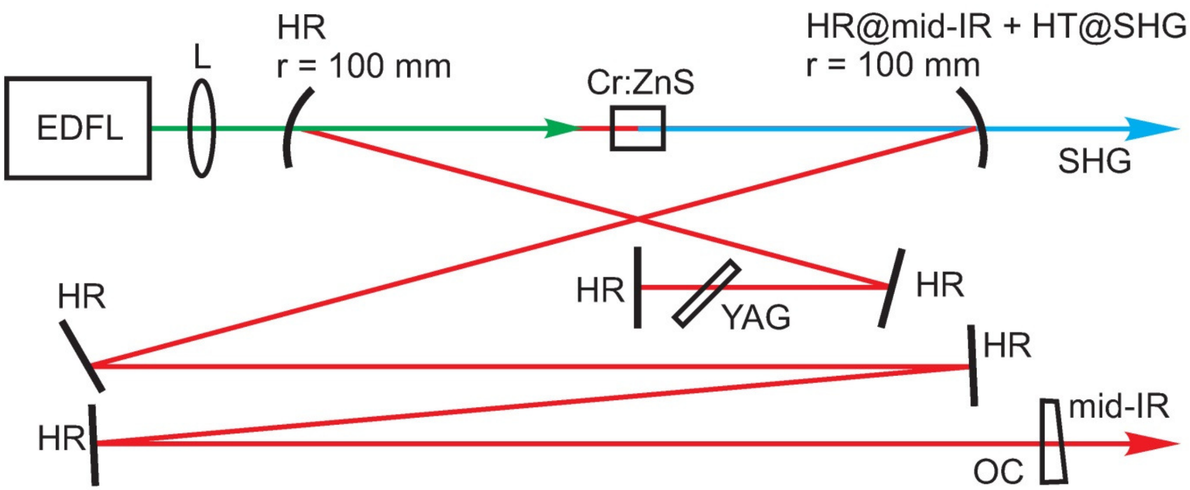
Kerr-lens mode-locked polycrystalline Cr^{2+}:ZnSe/ZnS lasers

Motivation

- Power scaling of mid-IR fs oscillators
- Investigation of three-wave mixing in polycrystalline Cr:ZnS/ZnSe in femtosecond regime

Approach

- Mounting of polycrystalline Cr:ZnS/ZnSe at normal incidence
  - ✓ Reduced thermal optical effects
  - ✓ Increased pump, laser intensity
  - ✓ Enables use of long gain element with high pump absorption



Schematic of Kerr-lens mode-locked Cr:ZnS laser setup

Features:

- Standard EDFL pump at 1567 nm
- 5-mm long AR coated Cr:ZnS with 89% pump absorption
- Asymmetric 1.9 m long resonator (79 MHz mode spacing)
- 2.3 μm central wavelength
- Dispersion management by YAG plate, dispersive mirrors
- GDD = -1500 ± 400 fs^2

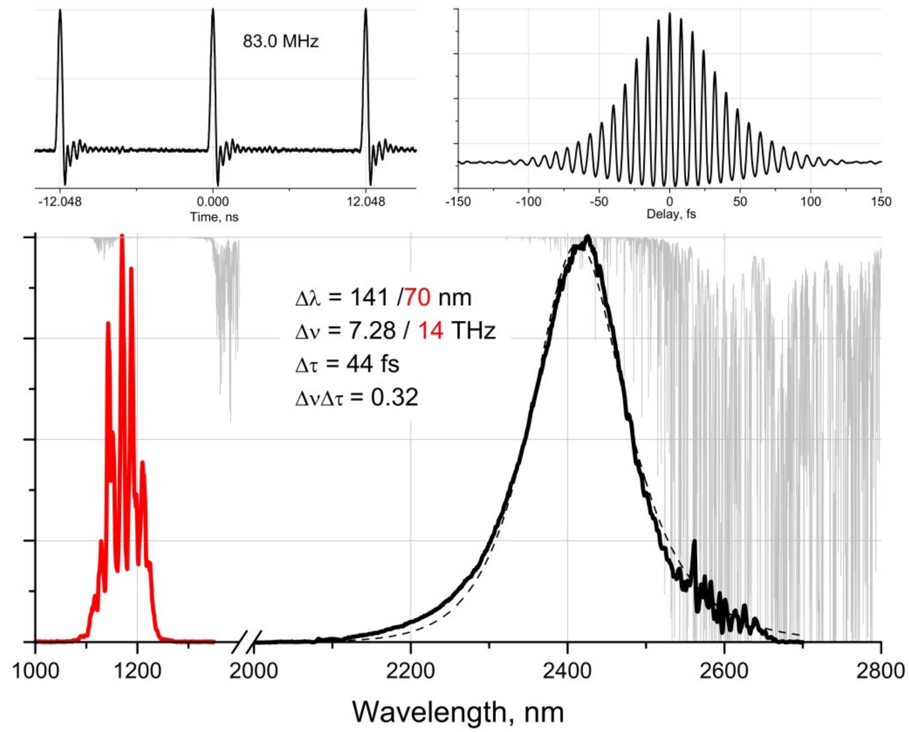
Kerr-lens mode-locking of polycrystalline Cr:ZnS/ZnSe laser *S. Vasilyev et al. Opt. Express 22, 5118 (2014)*

Kerr-lens mode-locked polycrystalline Cr^{2+}:ZnSe/ZnS lasers

Main results

(for different laser configurations)

- Up to 2.0 W mid-IR average power
  67 fs pulses, 95 MHz rep. rate
- 20% pump efficiency
- Up to 44 fs mid-IR pulse duration
  at 0.5-0.6 W average power, 79 MHz rep. rate
- Up to 340 kW peak power
  22 nJ, 55 fs pulses, 79 MHz rep. rate
- Up to 0.3 W SHG output
- Up to 14 THz SHG spectral bandwidth



Typical fs pulse train, autocorrelation trace, emission spectrum of mode-locked Zr:ZnS/ZnSe lasers (dashed line shows sech fit)

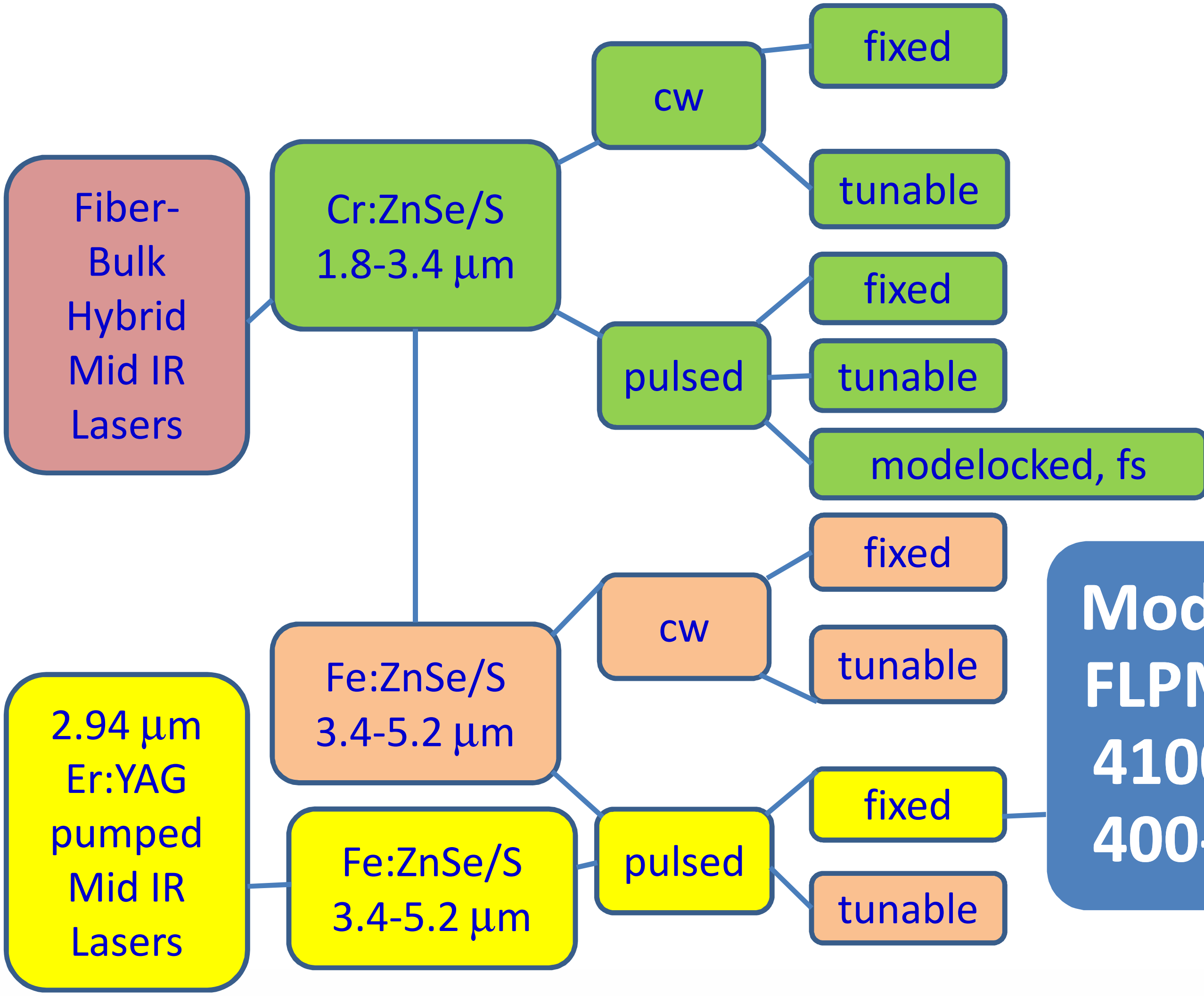
Outlook

- 4 W Cr^{2+}:ZnS/Se oscillators
- GW peak power Cr^{2+}:ZnS/Se CPAs
- Single-optical-cycle Cr^{2+}:ZnS/Se oscillators

Mid-IR, SHG, THG, FHG beams on IR-sensitive card

IPG PHOTONICS

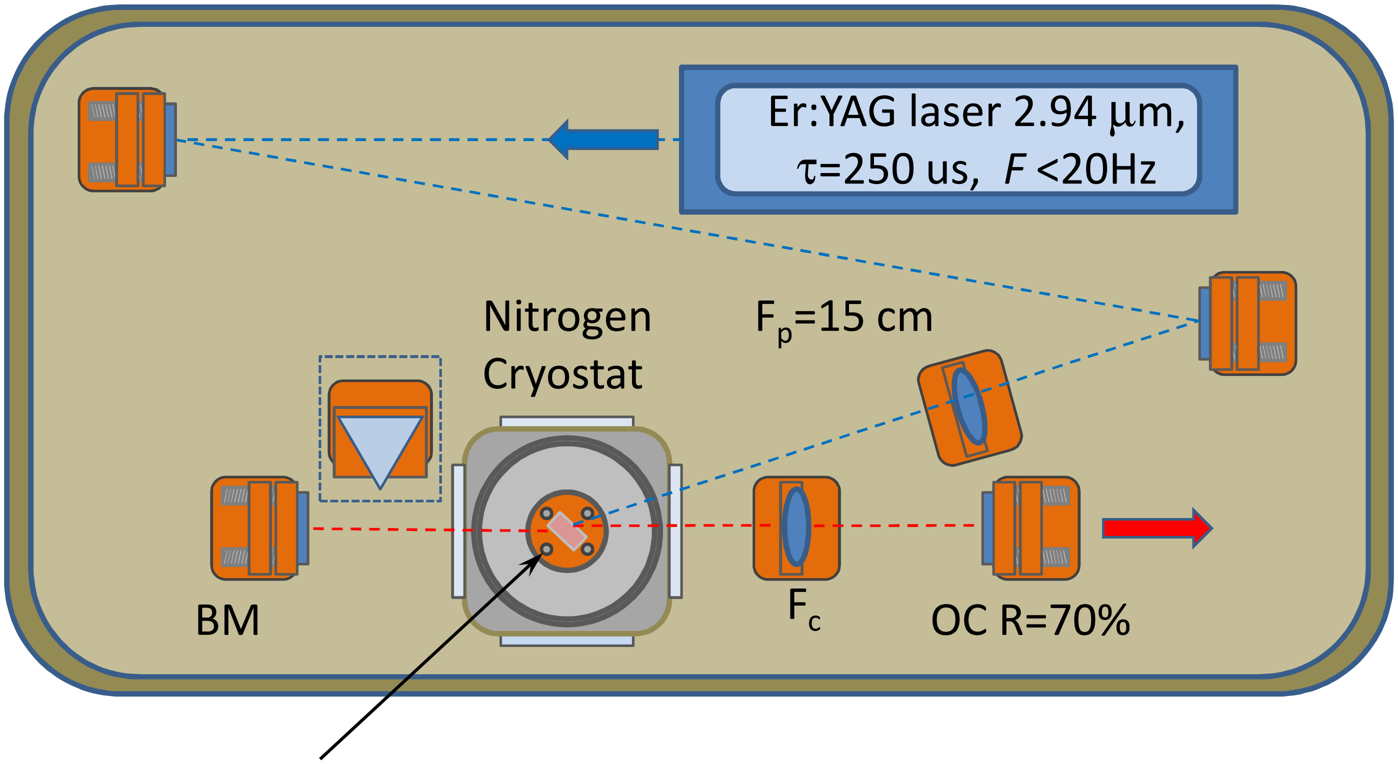
High Energy Free-Running Pulsed Fixed Frequency Fe:ZnSe Laser



Model FLPM-4100-400-4

- **Any wavelength within 3.9-5.2µm**
- **High Output Energy >400 mJ**
- **Pulse Duration 200 µs**
- **Max. Repetition Rate >20 Hz**

Optical Scheme of Fe:ZnSe pulsed Laser



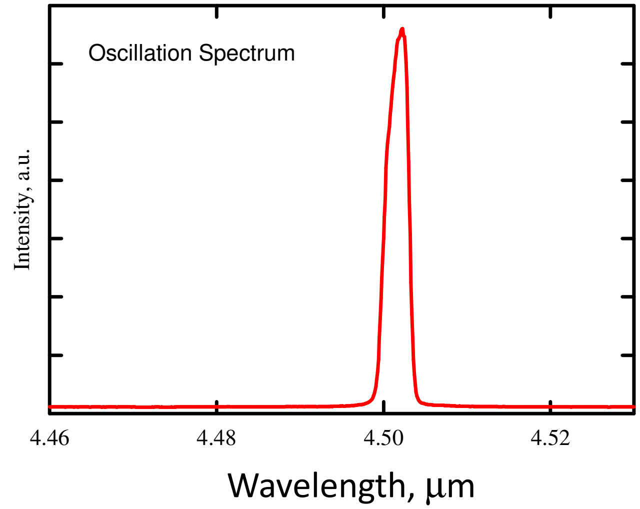
Fe^{2+} doped ZnSe polycrystalline with iron concentration of $1.5x10^{19}$ cm^{-3}

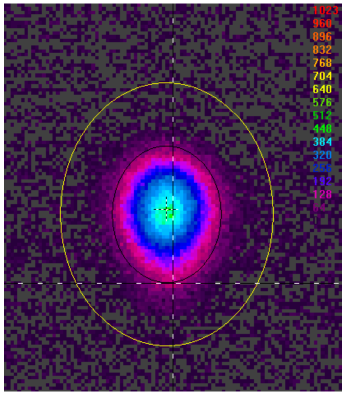
IPG PHOTONICS

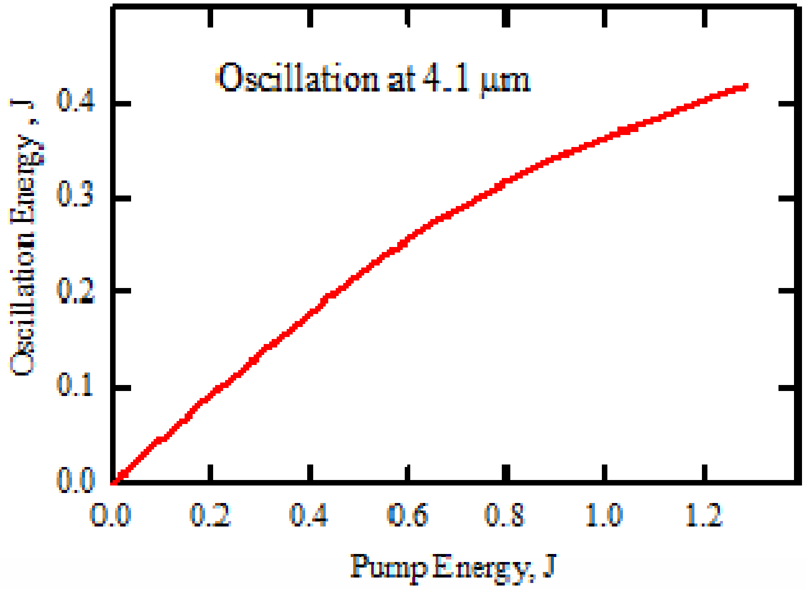
High Energy Free-Running Pulsed Fixed Frequency Fe:ZnSe Laser

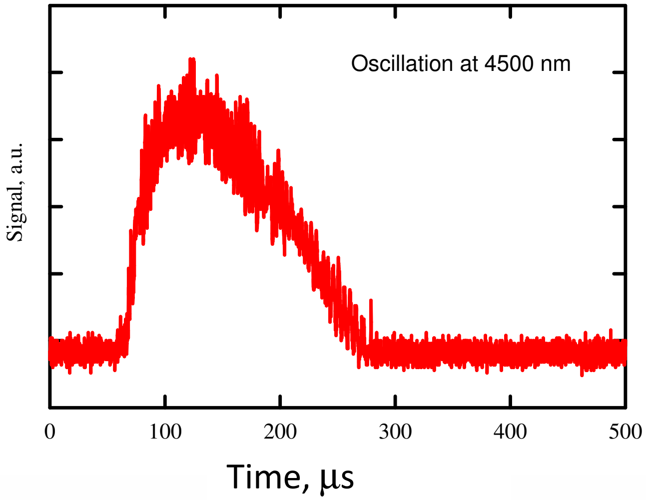
Model FLPM-4100-400-4

- Any wavelength within 3.9-5.1µm
- High Output Energy >400 mJ
- Pulse Duration 200 µs
- Max. Repetition Rate >20 Hz





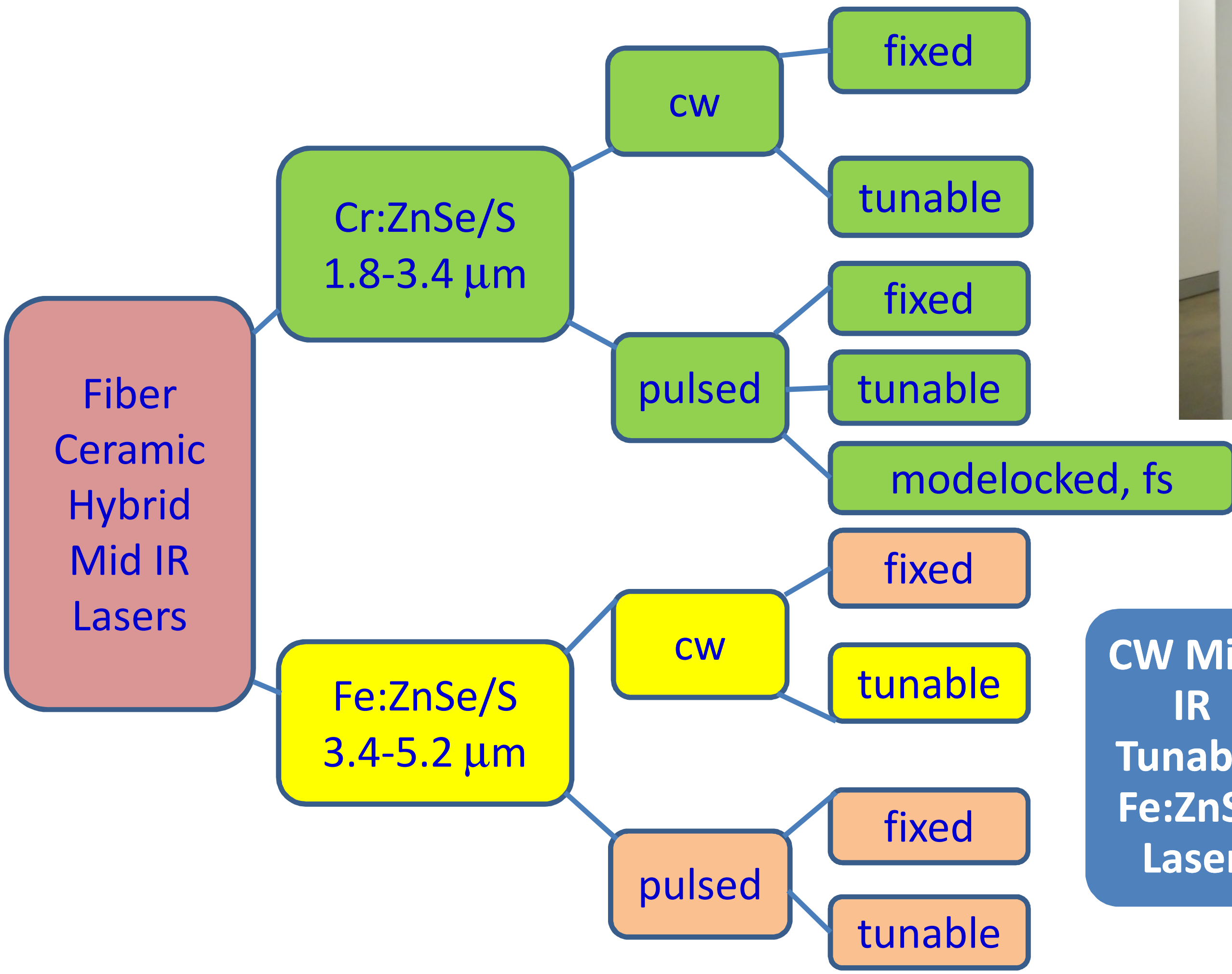




- Spectroscopic
- Sensing
- Medical
- Defense
- OPO seeding and pumping

IPG PHOTONICS

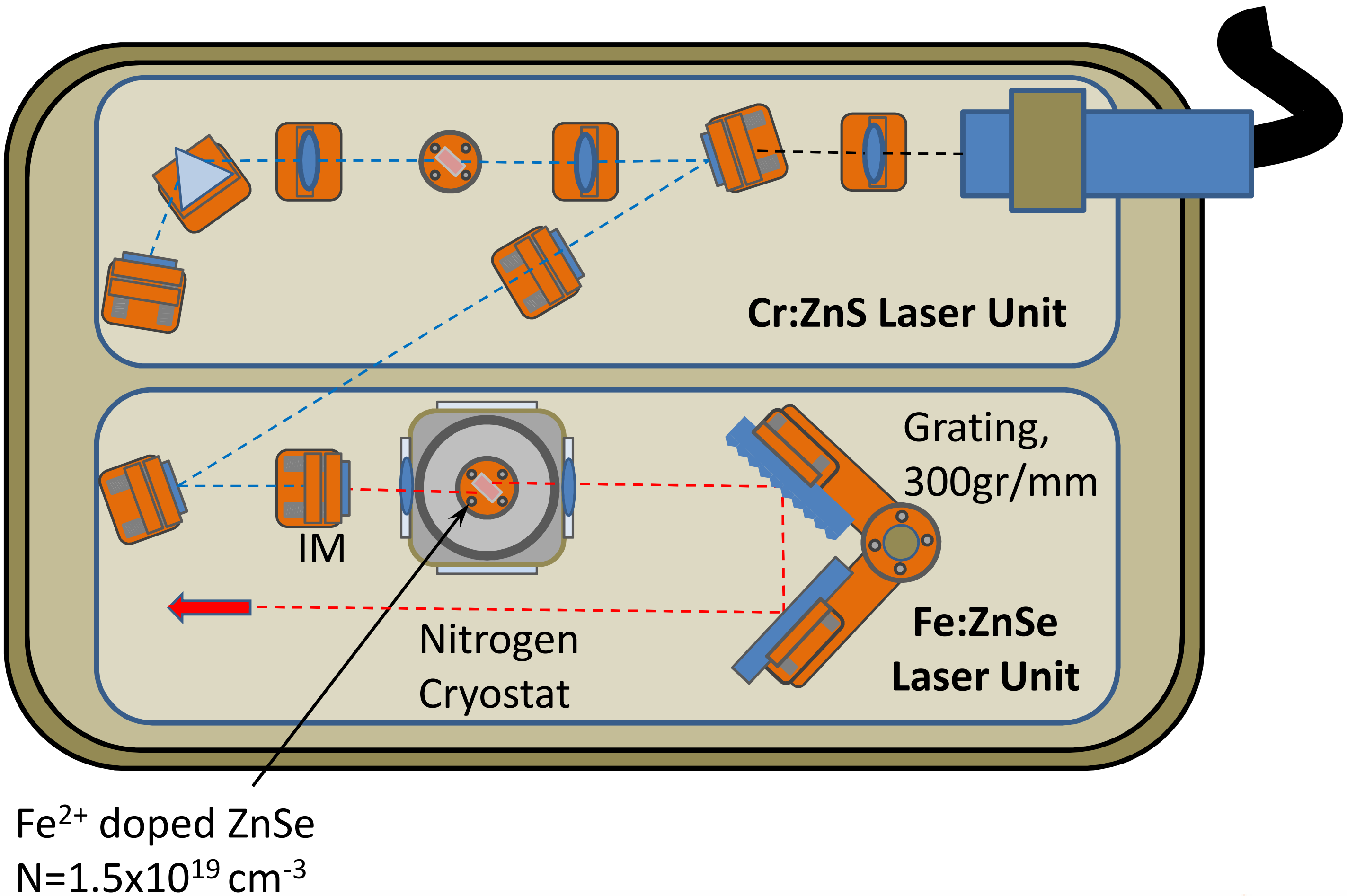
CW Tunable Fe:ZnSe Laser



CW Mid-IR Tunable Fe:ZnSe Laser

- **Any wavelength within 3.7-4.8µm**
- **Output Power > 300 mW**

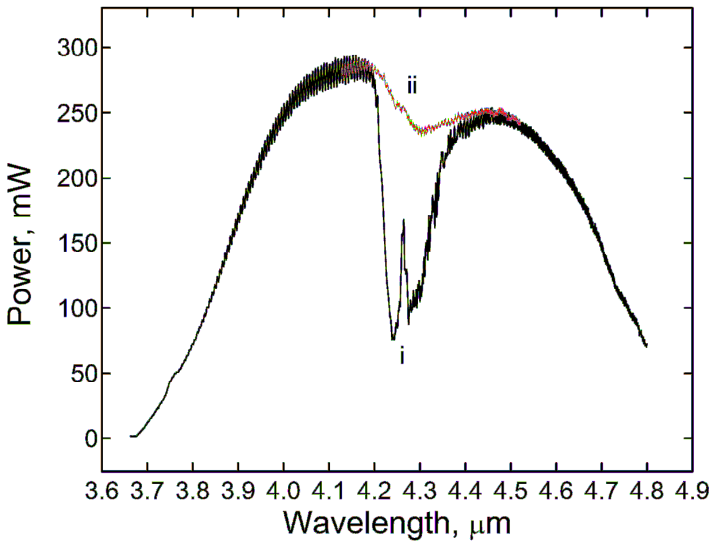
CW Tunable Fe:ZnSe Laser



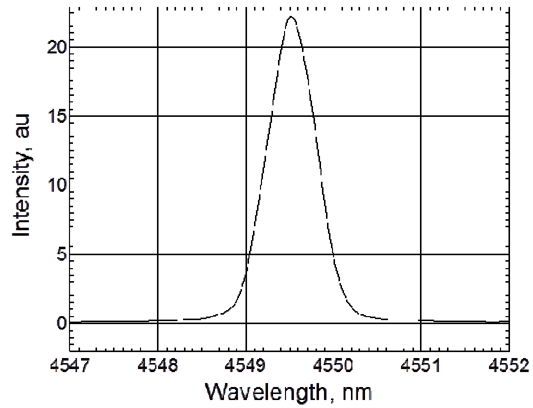
CW Tunable Fe:ZnSe Laser
FLT-4200/100-0.3

Any wavelength within 3.7-4.8µm

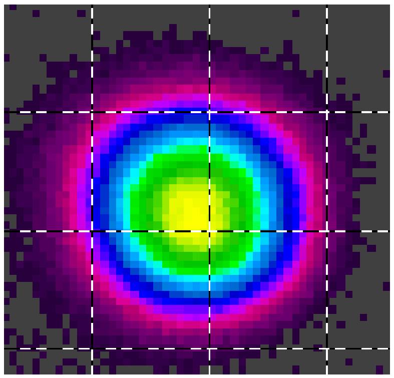
Output Power up to 1.5 W



Typical tuning curve (i) in ambient atmosphere (ii) purging with AR



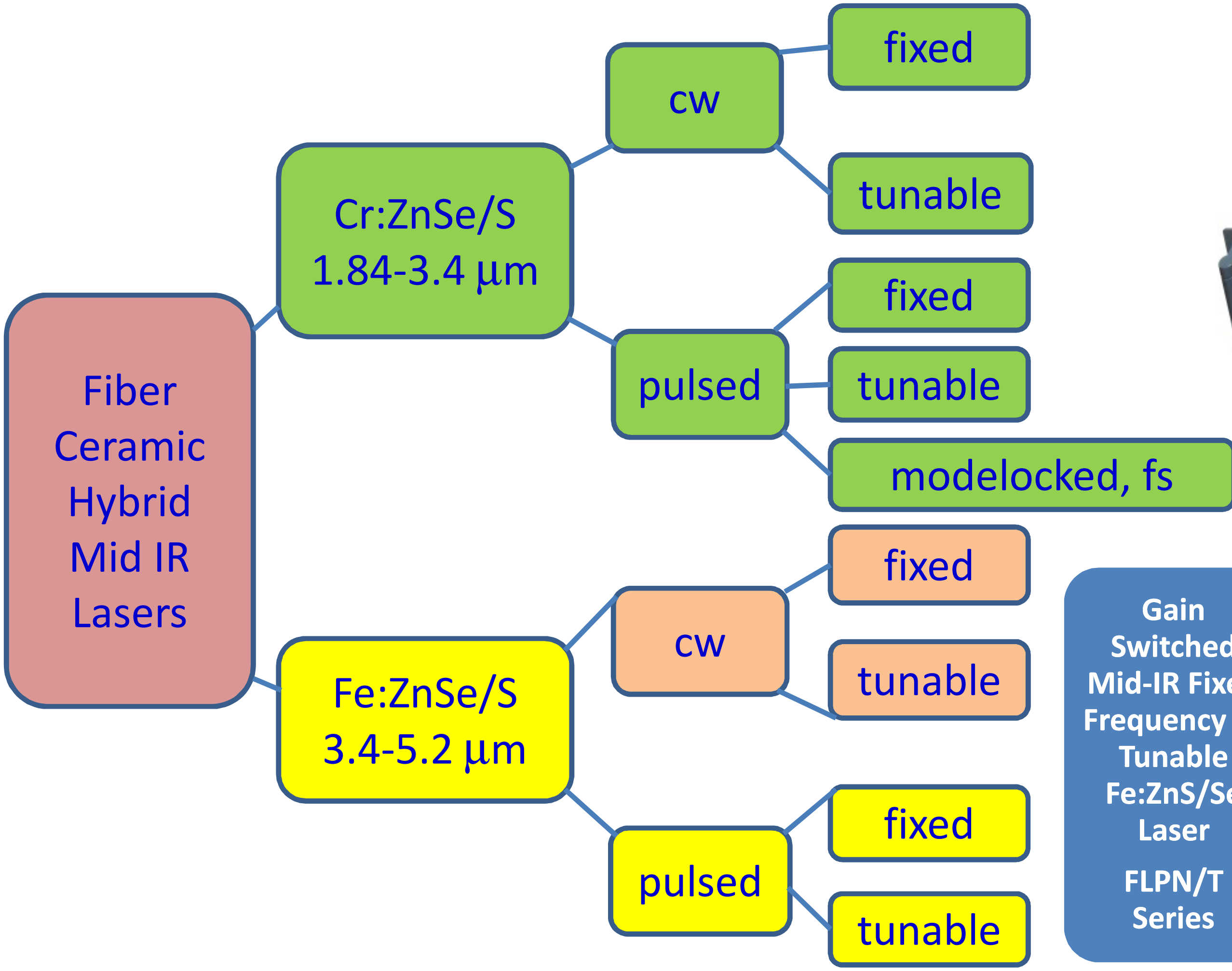
Linewidth



Beam profile

- Spectroscopic
- Sensing
- Medical
- Defense
- OPO seeding or pumping

Gain Switched Mid-IR Fixed Frequency or Tunable Fe:ZnS/Se Lasers

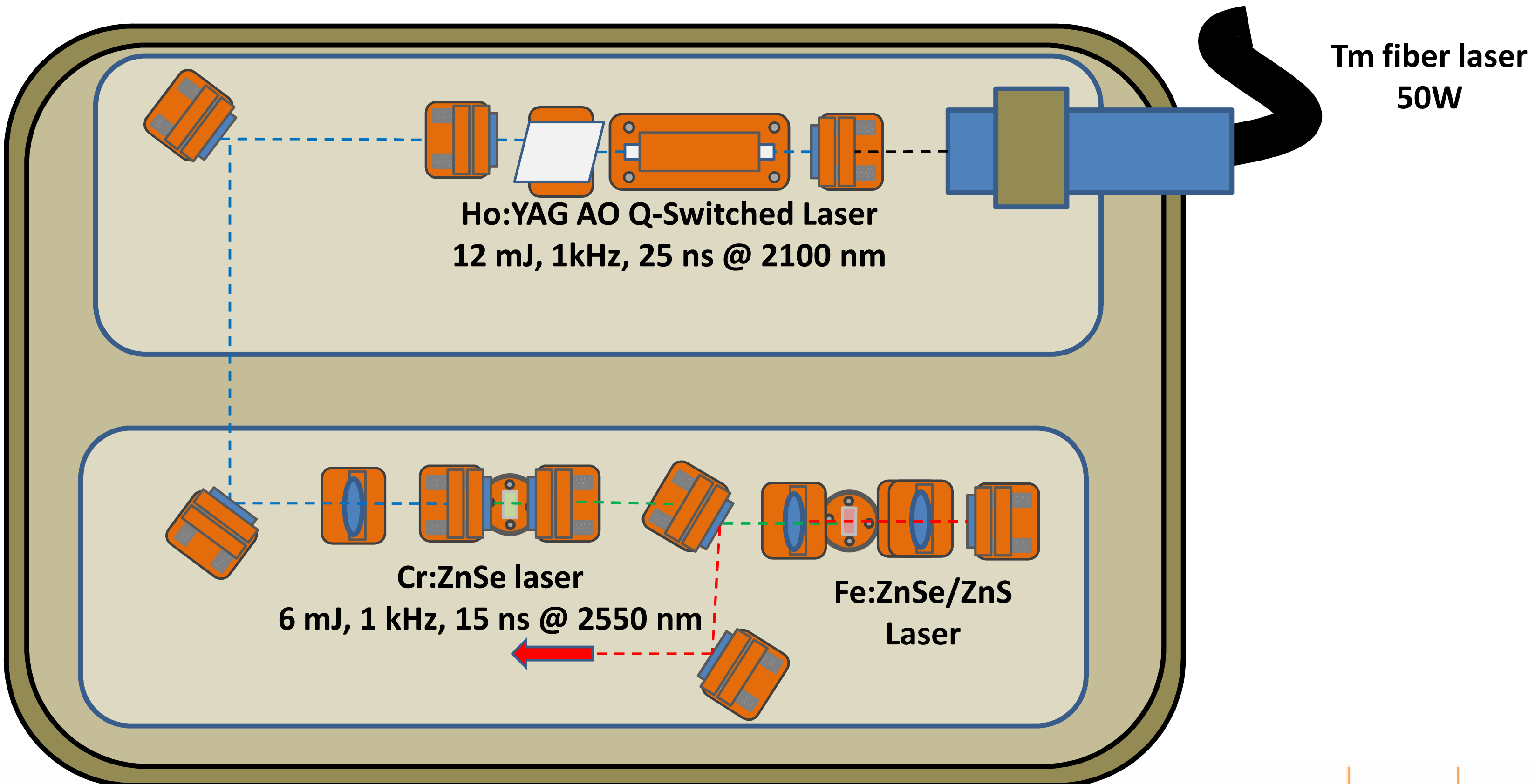


Gain Switched Mid-IR Fixed Frequency or Tunable Fe:ZnS/Se Laser

FLPN/T Series

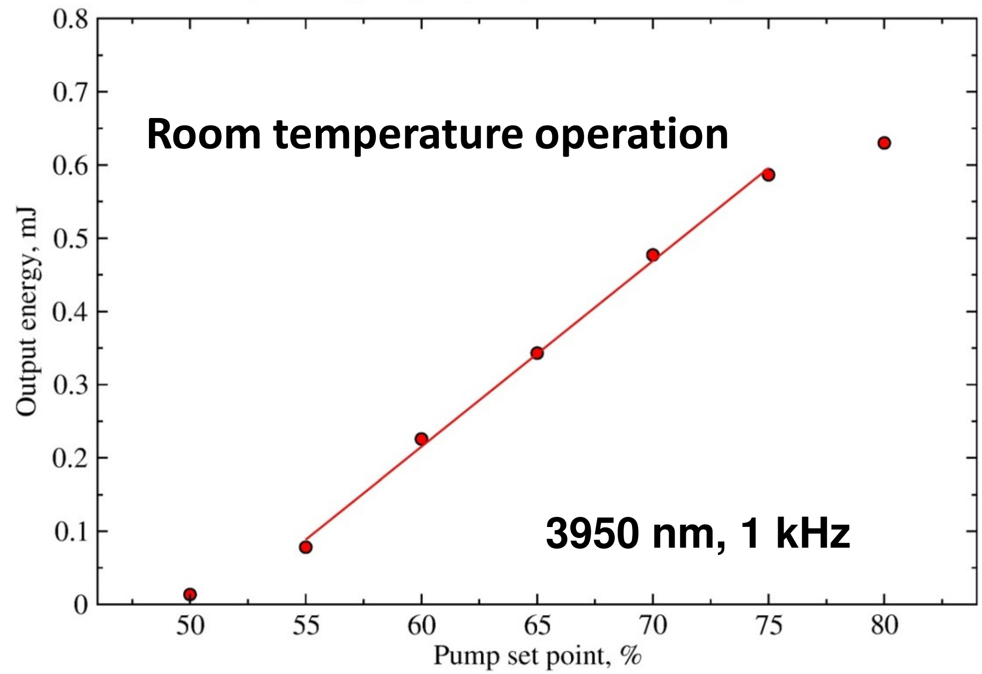
- Output wavelength within 3.6-5.0µm
- Output Energy >0.5 mJ
- Pulse Duration 2-20 ns
- Repetition rate 0.1-1 kHz
- TEM_{00}

Gain Switched Mid-IR Fixed Frequency or Tunable Fe:ZnS/Se Lasers



Gain Switched Fixed Frequency or Tunable Fe:ZnS/Se Lasers FLPN-3950-1 Series

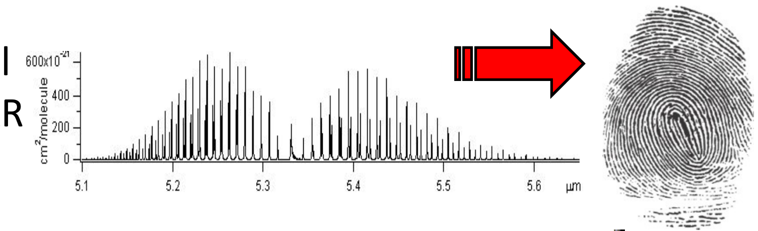
- Output wavelength within 3.6-5.0µm
- Output Energy >0.5 mJ
- Pulse Duration 2-20 ns
- Repetition rate 0.1-1 kHz
- TEM_{00}



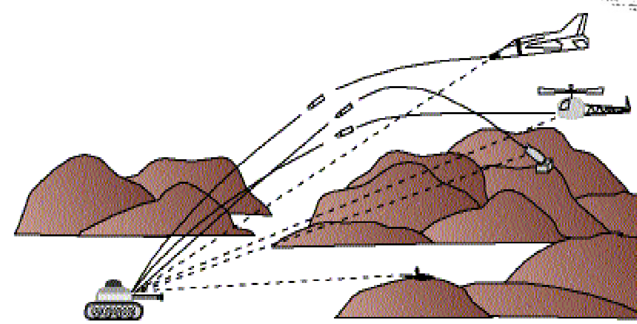
- Medical
- Materials Processing
- Environmental Monitoring
- Sensing
- Industrial Process Control
- MALDI Mass Spectroscopy

Mid IR Applications

- **Materials processing**: plastics cutting, welding, marking, drilling; forming of plastics, curing of coatings, ICs lift-off from Si sub.
- **Medical**: diagnostic, therapeutic, surgical
- **Spectroscopy**: molecular identification and dynamics; noninvasive nondestructive measurements; chemical agent and biomolecular sensing/ detection
- **Sensing and Imaging**: bioimaging, art imaging, hyperspectral imaging, thermography, tracking/ homing, night vision, LIDAR



- **Defense:** infrared countermeasures, target illumination and designation



- **Meteorology / Climatology / Astronomy**
- **Communications**
- **Pumping OPG/OPO**
- **X- ray Generation**

Conclusions and Outlook

- Chromium and Iron doped ZnSe and ZnS lasers have come of age, and, arguably, represent nowadays the most effective route for lasing over 1.9-5 um spectral range with multi-watt average power, peak power up to 1 GW, multi-Joule energy and pulse durations up to 40 fs.

- Future progress of Cr- and Fe-doped II-VI lasers in terms of extending spectral coverage over 3-4 μm and 5-9 μm depends on a search of new, low-phonon-cutoff Cr- and Fe-doped binary and ternary II-VI semiconductors bulk materials.

Conclusions and Outlook

- ❑ Future improvements in output power will depend on new schemes of thermal management of gain elements including utilization of fiber, waveguide and disk geometry.

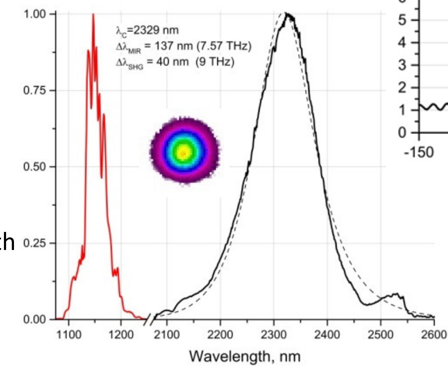
- ❑ Future Improvements in technology of hot-pressed ceramic II-VI compounds can stimulate design flexibility of the laser elements with high optical quality (undoped ends, , gradient of dopant concentration, etc) important for development of efficient, high performance lasers with output power and energy scaled-up to hundreds of Watts and tens of Joules.

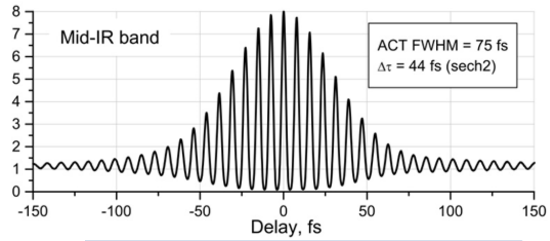
Thank you for your attention!

Femtosecond Mid-IR Laser

Model CLPF-2400-20-60-2

- Output power up to 2W
- Pulse duration from 50 fs
- Custom fixed central wavelength
- Wavelength tuning
- SHG option (up to 0.3W
- Power amplifier Option





High Power Narrow Line Cr^{2+}:ZnS/Se Tunable Laser

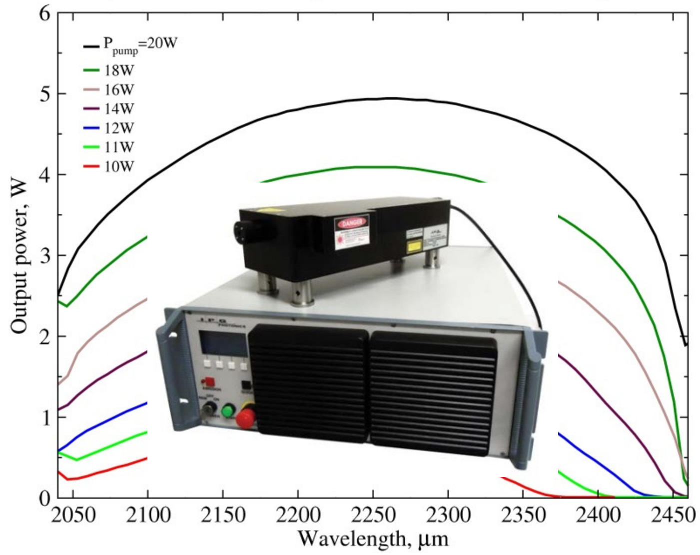
MODEL: CLT--**2400/1000-4**

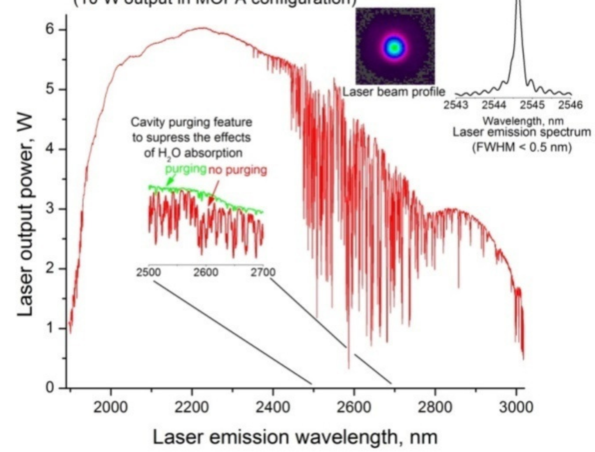
- Multi-Watt (20W) Output Power
- Narrow Linewidth, < 0.1 nm available
- Large tuning range with a single set of optics (any wavelength within 2000 - 3000 nm tuning range is available)

High Power, Tunable, Single Frequency Mid-IR Product Line

Model CLT-2200/500-5

- Multi-Watt Output Power
- Narrow Linewidth, <10 MHz available
- Large tuning range with a single set of optics (any wavelength within 2000 - 3000 nm tuning range is available upon request)





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