Fluorescence Cooling and Nonradiative Losses in Erbium-Doped Optical Materials in the 1.5 Micron Spectral Region

Nicholas J. Condon, Steven R. Bowman, Shawn O'Connor

Optical Sciences Division, Naval Research Laboratory, Washington D.C.

Carl E. Mungan

Department of Physics, United States Naval Academy, Annapolis, MD

Richard S. Quimby

Department of Physics, Worcester Polytechnic Institute, Worcester, MA

Michael J. Myers

Kigre, Inc., Hilton Head Island, SC

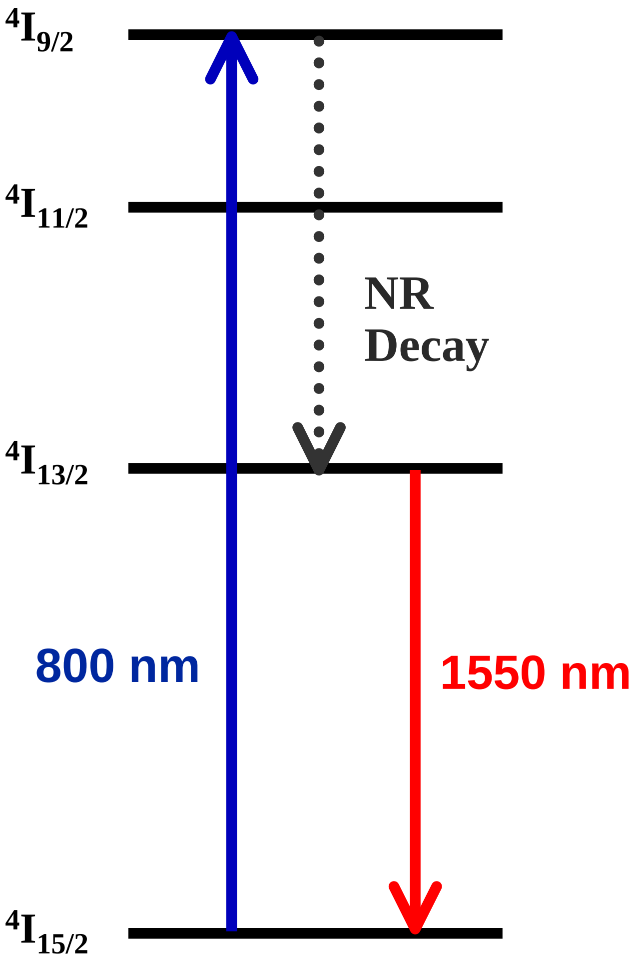
John Vetrovec

Aqwest, Inc., Larkspur, CO

This research was supported by the Office of Naval Research.

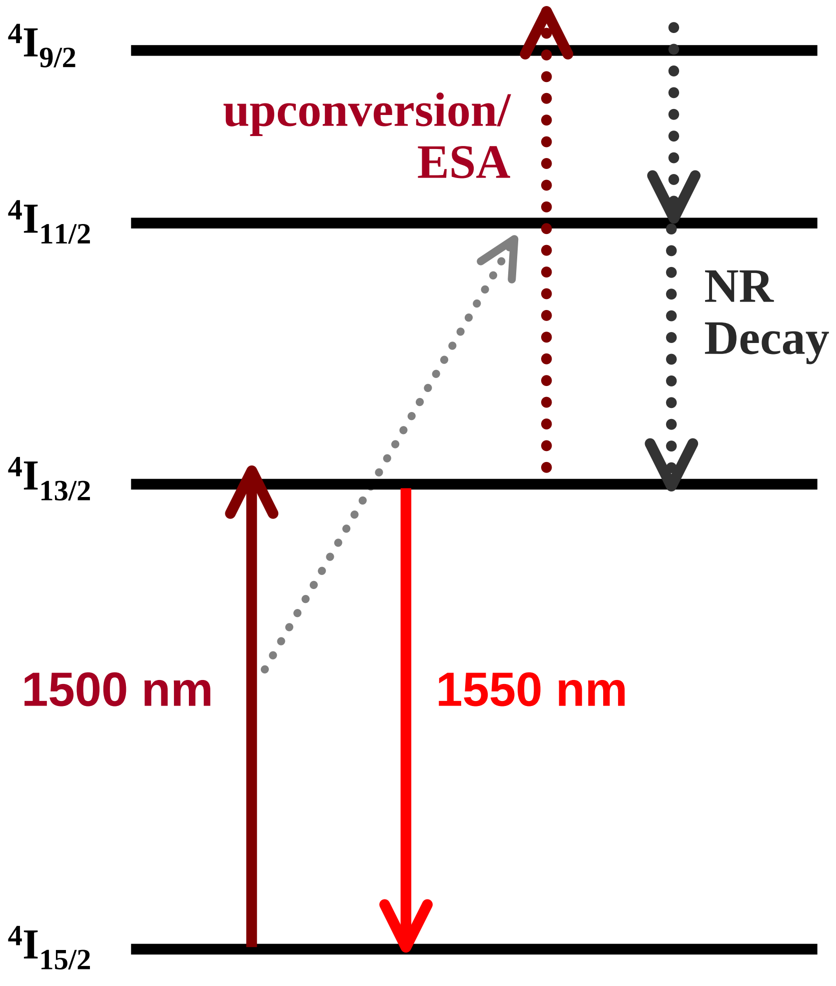
1.55 µm Er^{3+} Lasers

- Interest in high-power Er^{3+} lasers operating in "eye safe" region near 1550 nm
- Traditionally pumped with 800 nm diodes
- High quantum defect leads to conversion of >40% of the pump power into heat
- High heating limits high-power performance

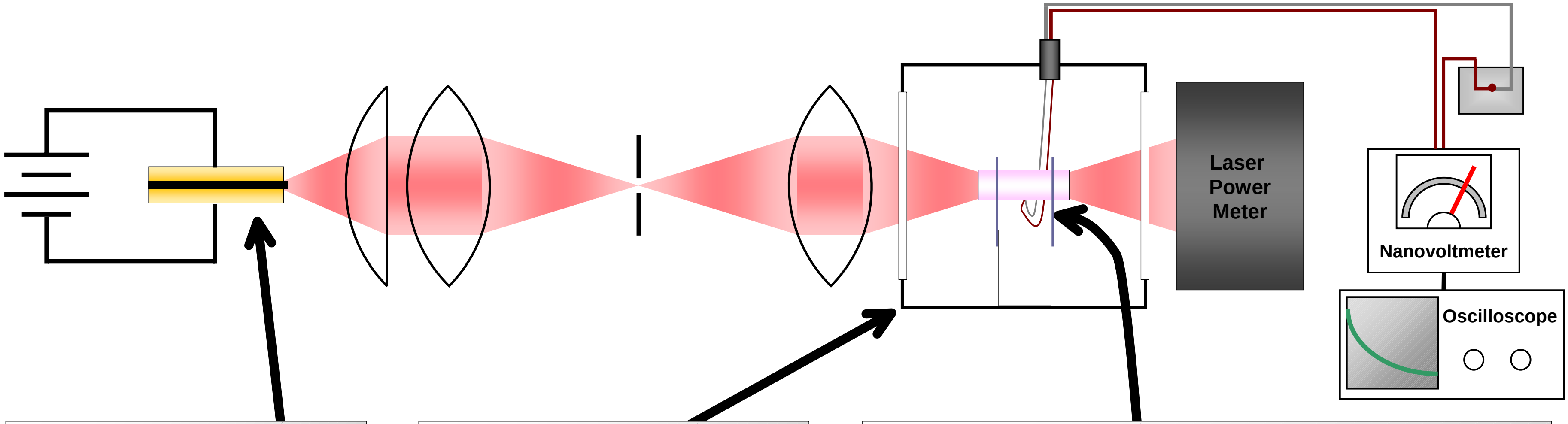


Resonantly-Pumped 1.55 μm Er^{3+} Lasers

- Recent advances in diode technology have made available diodes ~1500 nm
- Resonant or near-resonant pumping reduces heat load due to quantum defect
- Upconversion and ESA can lead to heating in oxide hosts
- Materials with low upconversion/ESA and low phonon energies can minimize heating



Experimental Setup



Laser Diode

- ~1550 nm
- 4-7 nm linewidth
- ~200 mW incident on sample
- 3 diodes with different nominal wavelengths available
- temperature tuning provides 5 total wavelengths

Sample Chamber

- designed to minimize nonradiative heat transfer
- evacuated w/CaF2 windows
- sample is supported by the edges of two pairs of crossed cover slips
- sample is 3 mm diameter rod, polished on barrell and faces

Thermocouple

- type T (copper-constantan), 0.001” wires for minumum conduction
- junction contacts sample at midpoint
- reference junction is held in an isothermal block

Data Collection

- Laser illuminates sample until they equilibrate
- Transmitted laser power measured using laser power meter
- Laser is shut off, and the relaxation transient is recorded every 0.2 s for 200 s

Heat Load Measurement Methods

Method	Photothermal Deflection	Thermal Imaging	Thermocouple
Sensitivity	HIGH	LOW	HIGH
Beam Quality Required	HIGH	LOW	LOW
Sample Quality Requried	HIGH	LOW	LOW
Surface Quality Required on Non-Illuminated Faces	LOW	HIGH	HIGH
Interference from Population Effects	YES	NO	NO
Works for Low Emissivity Materials	YES	NO	YES
Contacts Sample	NO	NO	YES
Experimental Complexity	HIGH	LOW	LOW

Samples Analyzed

Yttrium Aluminum Garnet (YAG)

- Standard laser host material
- 2% Er^{3+} doping
- Rod, 3 mm diameter by 20 mm long, polished on barrel and faces

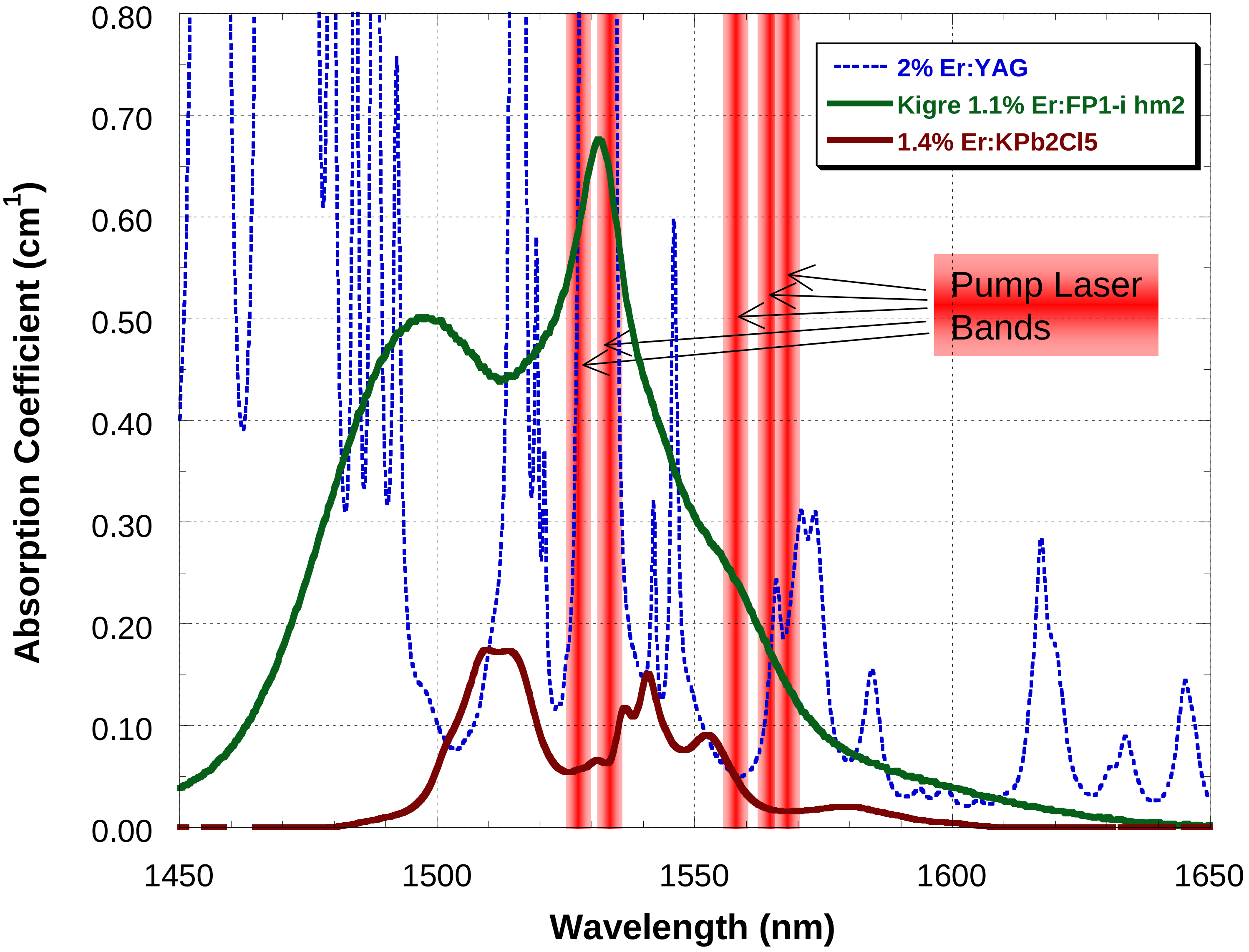
Optical Glasses

- Samples obtained from Kigre, Inc.
- Phosphate and fluorophosphate glasses in several formulations
- Doped with 1.1% Er^{3+} or codoped with 2.2% Er^{3+} and 2.5 Yb^{3+}
- Rods, 3 mm diameter by 20 mm long, polished on barrels and faces

Potassium Lead Chloride (KPb_2Cl_5)

- Grown in-house
- Low phonon energy (200 cm^{-1} vs. 700 cm^{-1} for Er:YAG)
- Invisible to thermal cameras
- Low overlap between $^4I_{13/2}$ and $^4I_{9/2}$ ESA band leads to very small upconversion coefficients (100x lower than Er:YAG)
- Good candidate for resonant pumping
- $[Er^{3+}] = 6.3 \times 10^{19}$ ions/cc, or 1.4%
- Rod, 3 mm diameter by 13.4 mm long, polished on barrel and faces
- Twin-free and highly transparent

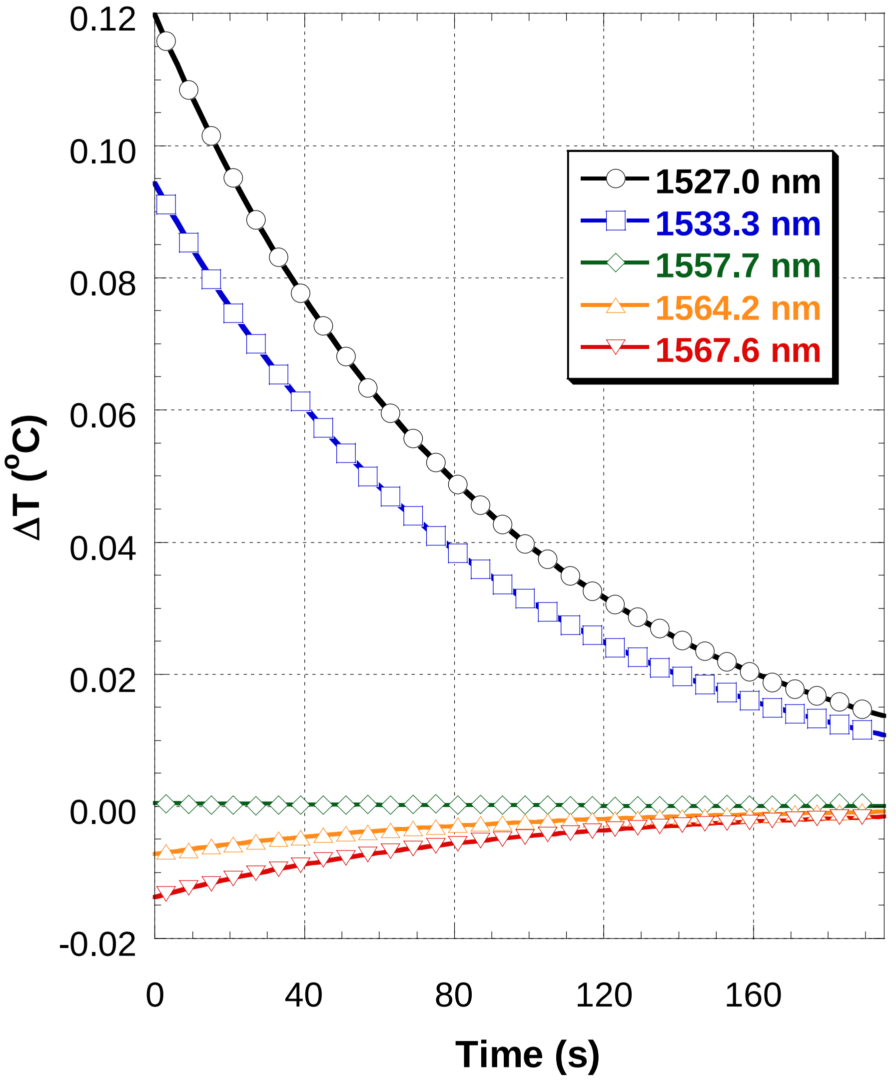
Absorption Spectra



Cooling in $\mathrm{Er{:}KPb_2Cl_5}$

- Optical Cooling Observed in $\mathrm{Er^{3+}{:}KPb_2Cl_5}$
- Crossover wavelength, $\lambda_c \approx 1558$ nm
- Nonradiative losses of ~1.2%

- Each curve is the average of 5 measurement runs
- A linear term was removed from the data to correct for chamber temperature drift
- Curves offset so $\Delta T = 0$ at $t = \infty$
- Data were fit to an exponential with $\tau_c = 90$ s
- Every 30th data point is displayed



Results: Glass and YAG

- The Er:glass and Er:YAG samples showed heating at all wavelengths
- Signal levels were much higher (~1-5°C vs. <0.2°C) due to greater absorption and higher nonradiative loss
- Er-doped fluorophosphate glasses showed ~5% nonradiative loss, while phosphate glasses and codoped samples were much lossier
- 2% Er:YAG showed a ~4% nonradiative loss
- **As ESA and upconversion are intensity-dependent, these losses will likely increase at higher powers**

Sample	**[Er^{3+}] (10^{20} cm^{-3})**	**Heat Load**
1.1% Er MM2 Phosphate	**0.89**	**17-19%**
1.1% Er MM4 Fluorophosphate	**1.23**	**5.0-6.5%**
1.1% Er FP1-i hm2 Fluorophosphate	**1.22**	**4.5-6.7%**
2.2% Er/2.5% Yb JD8813 Phosphate	**2.26**	**17-19%**
2.2% Er/2.5% Yb MM4 Fluorophosphate	**2.45**	**11-14%**
2% Er:YAG	**2.77**	**2.0-5.4%**
1.4% Er:KPb$_2$Cl$_5$	**0.63**	**(-0.4)-0.9%**

Summary

- Optical cooling was demonstrated for the first time from the ${}^4I_{13/2}$ state of Er^{3+}
- $Er{:}KPb_2Cl_5$ showed nonradiative losses of ~1.2%. This result is expected, given its low phonon energy and low upconversion coefficients.
- Er^{3+}-doped fluorophosphate glasses showed nonradiative losses of ~5%, while phosphate glasses and Er/Yb codoped samples showed significantly higher heating.
- Er:YAG showed nonradiative losses of 2-5%.